Arnold Schwarzenegger
Governor

MEASURING AND MONITORING PLANS FOR BASELINE DEVELOPMENT AND ESTIMATION OF CARBON BENEFITS FOR CHANGE IN FOREST MANAGEMENT IN TWO REGIONS

Changing from Even-Age Management with Clearcuts to Uneven-Age Management with Group Selection Harvests

PIER FINAL PROJECT REPORT

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PUBLIC INTEREST ENERGY RESEARCH
"Research Powers the Future"

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

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- Buildings End-Use Energy Efficiency
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- Renewable Energy Technologies

What follows is the final report for the Measurement, Classification, and Quantification of Carbon Market Opportunities in the U.S.: California Component project, contract number 100-98-001, conducted by Winrock International. The report is entitled *Measuring and Monitoring Plans for Baseline Development and Estimation of Carbon Benefits for Change in Forest Management in Two Regions: Changing from Even-Age Management with Clearcuts to Uneven-Age Management with Group Selection Harvests.* This project contributes to the PIER Energy-Related Environmental Research program.

For more information on the PIER Program, please visit the Energy Commission's Web site www.energy.ca.gov/pier, or contact the Energy Commission at (916) 654-4628.

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Abstract

The research discussed in *Measuring and Monitoring Plans for Baseline Development and Estimation of Carbon Benefits for Change in Forest Management in Two Regions: Changing from Even-Age Management with Clearcuts to Uneven-Age Management with Group Selection Harvests* was conducted to inform a larger-scale effort identifying the scope and efficacy of potential carbon sequestration projects in California. This project assessed the relative biomass carbon storage potential of forest management options at two study sites representing key timber production regions in California: Sierran mixed conifers at Blodgett Forest Research Station in the Sierra Nevada, and coastal redwoods at Jackson State Demonstration Forest. Each site assessment reflects a unique set of conditions, which determines the response to different management practices.

In the Blodgett Forest Research Station (BFRS) analysis, no carbon benefit was found for switching from clearcut to group selection harvests. However, if the project focused solely on shade-tolerant species, then a different outcome could emerge. In that case, a net carbon advantage would arise for the change in forest management, but this advantage would likely be small—not exceeding five tons of carbon per hectare (t C/ha) after 50 years.

In the *Jackson State Demonstration Forest* analysis, over one rotation of the modeled scenarios, even-aged management with group selections yielded slight carbon increases, from 337 to 645 tons over 23.9 hectares, in total forest carbon storage over clearcuts—an amount equivalent to an increase in carbon storage per unit area of 14 to 27 t C/ha.

Executive Summary

Objectives

The report serves to assess the relative biomass carbon storage potential of forest management options at two study sites representing key timber production regions in California; Sierran mixed conifers at Blodgett Forest Research Station in the Sierra Nevada and coastal redwoods at Jackson Demonstration State Forest (Figure S.1). Each of these site assessments is presented as a specific and independent case study and each reflects a unique set of conditions (e.g., species composition), which determines the response to different management practices.

Figure S.1. Location of Jackson Demonstration State Forest and Blodgett Forest Research Station in California

Outcomes

Both forest sites have a set of forest measurements on an extensive network of permanent plots. For the work reported here, additional field data to be used with these plots were collected so that meaningful estimates of the potential carbon benefits from implementing the changes in forest management from conventional clear-cuts to group selection cuts could be developed.

Blodgett Forest Research Station

Blodgett Forest Research Station (BFRS) was visited in October 2003 to collect supplementary data to allow data from the BFRS's network of permanent plots to be used for carbon analyses. Data were collected on litter and duff depth and biomass, on soil carbon stocks and on dead wood densities.

Analyses of the BFRS permanent plots alongside literature reports permitted the creation of growth curves for regeneration growing in a clearcut, in a group selection or around the border of a canopy opening. The plot data allowed development of relationships between forest age or aboveground carbon biomass and forest floor, standing and lying dead wood and the carbon stocks belowground in roots. There was little relationship between forest age and soil carbon stocks and so soil carbon was emitted from this analysis.

No carbon benefit was found here for switching from clearcut (*without-project case* or baseline) to group selection (*with-project case*) harvests. The trees directly bordering any opening benefit in terms of growth and per unit area; there are more of these trees for group selections leading to enhanced sequestration. However, the carbon benefit attained by these trees is outweighed by the higher growth rates and higher carbon sequestration of the regeneration growing in clearcuts as opposed to in group selections.

The analysis here focused on the average of all commercial species grown at BFRS including both shade tolerant and shade intolerant species. If just the shade tolerant species were the focus then a different outcome could emerge. Species such as white fir and Douglas fir do not grow at a significantly slower rate in 0.6 ha group selections than in clearcuts and there is even evidence for white fir that growth could be faster in the group selections (York et al. 2004). In this case a net carbon advantage would arise for the change in forest management but this advantage would likely be small - not exceeding 5 t C/ha after 50 years.

Jackson Demonstration State Forest

The JDSF was visited in February 2004 to collect data required for biomass estimations. Measurements were made of trees in and around clearcuts and group selections and of dead wood, litter, understory and soil carbon.

Growth curves for coastal redwood at JDSF were developed from existing empirical yield tables. Field measurements drove the calibration of models predicting the accumulation of dynamic forest carbon pools including litter and downed dead wood stocks. Standing dead wood, understory vegetation, and soil carbon showed no appreciable changes with management or stand age. Significant differences in post-harvest growth were found between regeneration in group selections and clearcuts and between residual edge trees and interior matrix trees. These findings were used to predict responses in forest biomass with change in management practices.

Over one rotation of the modeled scenarios for JDSF, even-aged management with group selections (*with-project case*) yielded slight increases, from 337 to 645 tons over 23.9 hectares, in total forest carbon storage over clearcuts (*without-project case* or baseline). This is equivalent to an increase in carbon storage per unit area of 14 to 27 tons C per hectare.

As in the model for BFRS, results are sensitive to (1) the magnitude of the edge tree growth response, (2) the duration of the edge tree growth response, (3) the area of residual forest experiencing edge tree conditions, (4) the magnitude of the growth decrease of regeneration in the group selections, and (5) the duration of the growth decrease of regeneration in the group selections.

In the case of JDSF, the advantage of group selections is due to the greater (4 X) edge tree response area in the stand under uneven-aged management, as well as the magnitude of the positive edge tree response (+ 60 to 72% increase in yield after 90 years) as compared with the diminished growth of the regeneration within the groups (- 35 to 50% reduction in yield after 90 years). Though uneven-aged management at BFRS resulted in a similar increase in edge tree area, the response of edge trees was not as large (+ 18 to 20% increase in yield after 60 years), muted due to the mix of shade-tolerant (e.g., white fir) and shade-intolerant (e.g., ponderosa pine) species at BFRS, as compared with the diminished growth of the regeneration within the groups (- 27 to 32% reduction in yield after 60 years).

Conclusions

The estimates provided here are assessments of the potential carbon benefits from changing harvest management from clearcut to group selection. In this report we have outlined details of the measurements and the types of analyses needed to calculate the with- and without-project carbon stocks when there are existing inventory data and how to consider the variance in calculating the number of plots required for measuring and monitoring (see Section 3). Where there are no existing inventory data additional measurements would be required, but the analyses would essentially be the same as those given here.

1.0 Introduction

The report serves to assess the relative biomass carbon storage potential of forest management options at two study sites representing key timber production regions in California; Sierran mixed conifers at Blodgett Forest Research Station in the Sierra Nevada and coastal redwoods at Jackson Demonstration State Forest. Each of these site assessments is presented as a specific and independent case study and each reflects a unique set of conditions (e.g., species composition), which determines the response to different management practices.

Both forest sites have a set of forest measurements on an extensive network of permanent plots. For the work reported here, we collected additional field data to be used with these plots so that we could develop meaningful estimates of the potential carbon benefits from implementing the changes in forest management from conventional clear-cuts to group selection cuts.

An important question in forest management as a means to mitigate GHG emissions is whether forests can be managed to maximize income from a combination of carbon credits and timber while at the same time to increase or maintain other environmental benefits. The forest management practice that we will investigate in this class of project types is the change from harvesting of large clear-cuts (≥20 acres) to group selection harvesting (1/4 – 2.5 acre clear-cuts).

To calculate carbon benefits from this changed forest management practice there are several steps that need to be accomplished:

1. Identify the current management activity (over last 10-20 years or so)— this represents the without-project activity or baseline; and identify the carbon stocks affected
2. Identify the change in management activity—this represents the with-project activity; and identify the carbon stocks affected
3. Simulate empirical model for with- and without-project activities
4. Estimate carbon benefits as the difference between the with-project carbon stocks and without-project carbon stocks
5. Assess the potential for leakage and estimate the likely leakage amount of carbon emissions, and adjust estimated carbon benefits accordingly.

1.1. Group selection harvesting

Forestry practices can be broadly divided into even-age and uneven-age management systems. Uneven-age management, though often characterized by slower growth and consequent financial disadvantage than even-age management, offers aesthetic and ecological appeal in capturing "historic" stand compositions and disturbance regimes.

Uneven-aged management includes single tree selections and group selections. Under single tree selections, a single valuable individual is extracted from the forest and the gap is filled by a newly growing tree. This is often employed in species diverse forests where the abundance of the most valuable trees may be relatively low. A disadvantage of single tree selections is that a significant quantity of damage is incurred in felling and extracting each tree, and less vigorous trees make up a higher proportion of the residual stand as the dominant individuals have been selectively culled.

Under group selection, groups of trees, the extent of which here is considered between 0.5 and 2.5 acres, are removed, broadly simulating treefall gaps derived from natural disturbances like windfall. Group selections are particularly advantageous with regard to the growing of shade tolerant species such as White Fir or Douglas Fir (York et al. 2003).

Despite the environmental and aesthetic benefits, group selection is not widely adopted in Californian forestry due to financial and logistical considerations (Rob York, personal communication 2003). In this section of the report, the envisaged carbon benefits are evaluated.

Two growth responses stemming from improved light environment following harvest interventions are often particularly notable: regeneration within the harvest gap and increased growth of standing edge trees. Compared with clear-cuts, a larger portion of the regeneration within group selections will compete for light and soil and water resources with existing adult trees adjoining the cut. Consequently, mean growth rates of regeneration in group selections is comparatively diminished. York et al. (2004) measured a 13.1 % decrease in height after five years for regeneration in 0.6 ha group selections relative to 8 ha clear-cuts. On any site following harvest, light conditions are dramatically improved for trees remaining on the edge of the cut, as well as reduced competition for water and nutrients. These edge trees often respond with increased diameter growth (York et al, 2004), particularly to be expected among shade-intolerant species. For equivalent total area harvested, uneven-age management with group selections, compared with even-age management with clear-cuts, results in a greater linear perimeter distance to be taken advantage of by edge trees. The relative balance of these two effects must be taken into consideration to determine the forest biomass carbon benefits of one management practice over another.

1.2. Modeling group selections and clear-cuts

The carbon benefits were examined by modeling an identical area of forest harvested using [1] a clear-cut (without-project) or [2] a network of group selection extractions (with-project). York et al. (2004) calculated that approximately 0.6 ha group selections maximize the advantages of small opening size (e.g., for shade tolerant species) whilst minimizing the disadvantages of constrained growth for Sierran mixed conifers. Group selections at JDSF averaged less than 2.5 acres or 1 hectare. Twenty acres or 8 ha is the typical size of clear-cuts in California. California Forest Practice Rules (California Department of Forestry and Fire Protection, 2003) dictate a maximum clear-cut size of 20 acres for tractor yarding, which may be increased to 30 acres where slopes < 30%. The comparative analysis carried out here will consider thirteen 0.615 ha group selections and one 8 ha clear-cut:

Group Selections	0.615 ha			
Clear-cuts	8 ha			
Same area in each treatment, therefore		13	0.615 ha group selections	= 8 ha
		1	8 ha clear-cut	= 8 ha

To maintain the group selections as separate entities it is dictated here that the distance separating groups is set at 30 meters, slightly less than half the group width where the group configurations are square. In order to assure this there must be a buffer of 15 m around each group. This buffer area for the group selections will determine the minimum total area required for the model:

$(78m + (2*15m))^2/10,000$	=	1.2 ha buffer/clearcut
X 13 clearcuts	=	15.9 ha
The total area for the model	=	8 ha for harvesting and 15.9 ha buffer
	=	23.9 ha

Therefore for both the clearcut and the group selection models the total area will be 23.9 hectares, which affords a 103 meter buffer surrounding the clearcut, again where the harvest configuration is square, conforming with California Forest Practice Rules (California Department of Forestry and Fire Protection, 2003) – "even-aged regeneration units … shall be separated by at least 300 ft. in all directions." Of this area, 8 ha are harvested.

This configuration results in 33 % of the modeled stand (i.e., management unit) harvested, slightly exceeding California Forest Practice Rules for uneven-aged management maximum of 20 % of the area harvested "covered by small group clearings" (California Department of Forestry and Fire Protection, 2003). This California Forest Practice Rule was "broken" in the analysis to allow for equal area harvested within a management unit of equal size.

The area bordering each harvest is further calculated to identify trees in the border stand afforded improved light conditions from the cut. The width of the border where increased growth is modeled is assumed to be equal to one crown width. For Sierran mixed conifers, a conservative value for crown width was set at 7.5 meters. A 90 year old redwood on site index 160 corresponds with height of 152 feet or ~50 meters (Lindquist and Palley, 1963), which corresponds with a crown radius of 6 meters Van Pelt in Noss, 2000), thus delimiting a border area of 12 meters width.

In both cases, equivalent total area of 0.615 ha group selections affords ~ 4 times the border area as that surrounding an 8 ha clearcut:

Where the width of the border area	= 7.5 m around the cut (BFRS)
around 0.615 ha groups	= 0.257 ha/group selection
X 13 groups	= 3.35 ha of border trees
around 8 ha clearcut	= 0.868 ha/clearcut
X 1 clearcut	= 0.87 ha of border trees

Where the width of the border area	= 12 m around the cut (JDSF)
around 0.615 ha groups	= 0.434 ha/group selection
X 13 groups	= 5.64 ha of border trees
around 8 ha clearcut	= 1.41 ha/clearcut
X 1 clearcut	= 1.4 ha of border trees

1.3. Leakage

Leakage occurs where the activities of a project lead to carbon losses outside the borders of the project.

The possibility of leakage can call into question carbon benefits reported from a project. Projects must thus demonstrate that anticipated benefits do not result in increased emissions outside of the project area due to displacement of activities.

In terms of a change in forest management practices, leakage could result if a project results in decreased harvest accompanied by increased harvest elsewhere to accommodate steady demand. In the uneven-aged management scenario under consideration, an identical amount of timber is harvested as in even-aged management, simply with different logistical and spatial arrangements. As switching management practices further has no bearing on the *allowable* intensity of harvest under California Forest Practice Rules (California Department of Forestry and Fire Protection, 2003), demand is identically satisfied and no leakage should result.

1.4. References

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2.0 Blodgett Forest Research Station

2.1. Background information

Blodgett Forest Research Station (BFRS) is situated in the Georgetown Divide in the Sierra Nevada mountains of California. The station predominantly consists of high site mixed conifer forest (Figure 2.1). The Michigan-California Lumber Company gifted the forest to the University of California in 1933 with the purpose of providing a research site and a site for the demonstration of practices to the public, industry and students of forestry (Olson and Helms, 1996).

Figure 2.1
Mixed Sierran Conifer Forest at BFRS

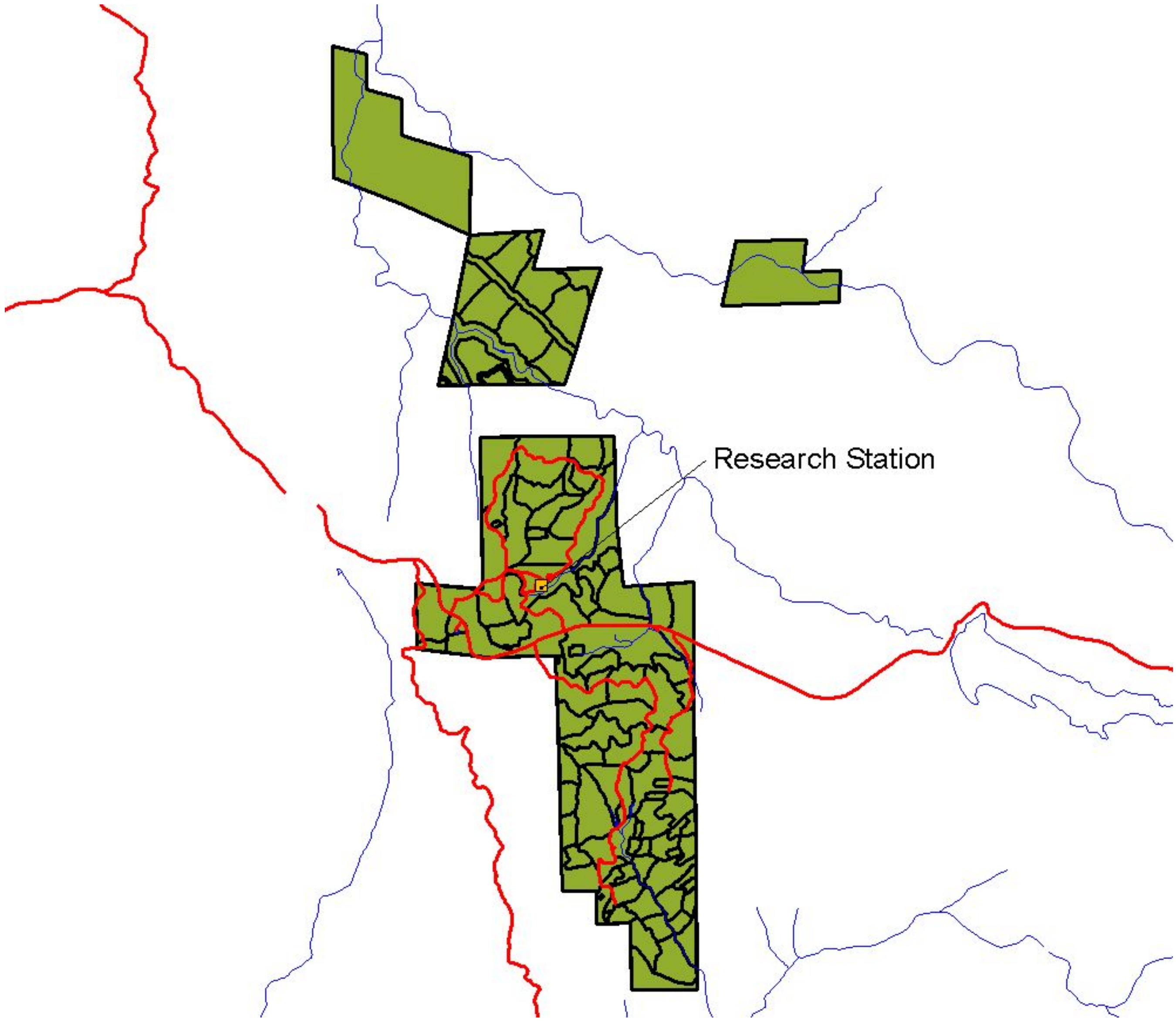


Figure 2.2
Blodgett Forest Research Station. The forest compartments are outlined.

The forest was harvested almost in its entirety in three entries in 1900, 1908 and 1912 then for approximately 50 years no large-scale commercial harvesting occurred as the forest regenerated (Olson and Helms, 1996). The forest is now divided into 109 compartments (Figure 2.2) dedicated to various management schemes including clearcut (e.g., Figure 2.3), shelterwood, single tree selection, variable retention, group selection and young and old growth preserves.

A system of permanent, comprehensive forest inventory plots was started in 1974 and completed in 1980. The system consists of a six-chain (396 feet) grid of 1/10 acre plots. There are approximately 700 of these plots with additional plots in streams, group selections and other areas of especial interest. During plots measurements (approximately every five years) a spectrum of environmental and physical data are collected including tree diameters and heights, dead wood measurements and depths of duff and litter (Olson and Helms, 1996).

A team from Winrock International visited BFRS in October 2003 to collect supplemental data required to increase the value of the Blodgett permanent plots for biomass estimations. Measurements were made to determine the relationship between litter/duff depth and biomass, dead wood volume and biomass and soil carbon storage.

The tree species commonly encountered at Blodgett are listed in Table 2.1.

Table 2.1. The tree species of BFRS. Commercially grown species are underlined.

Hardwoods	*Conifers*
Alder spp.	<u>Douglas Fir</u>
California Black Oak	<u>Giant Sequoia*</u>
Chinquapin	<u>Incense-cedar</u>
Dogwood	Lodgepole Pine
Canyon Live Oak	Nutmeg
Maple spp.	<u>Ponderosa Pine</u>
Pacific Madrone	<u>Sugar Pine</u>
Tanoak	<u>White Fir</u>
	Pacific Yew

*Giant Sequoia, though found in the region, is not native at BFRS.

Figure 2.3
Even-aged stands of ponderosa pine adjacent to BFRS

2.2. Biomass calculations for Blodgett forest

2.2.1. Estimating biomass components from forest inventory data

2.2.1.1. Aboveground live biomass

Aboveground biomass can be estimated using the permanent plot data from Blodgett forest or similar forest inventory data. In this study even-age plots were selected representing the full range of ages available at Blodgett (very young to fully mature forest); 140 plots were examined including 2,789 trees. These plots included measurements of diameter at breast height (dbh). Using the allometric regression formulae of Jenkins et al. (2003; Table 2.2) dbh was converted to biomass and subsequently to carbon biomass density (t C/ha). Using the equations produces per tree biomass values in kilograms. Dividing by 2,000 gives the value in metric tons of carbon (throughout this report carbon is assumed to equal biomass x 0.5). To calculate landscape scale values expansion factors must be used. The Blodgett team measures trees > 4.5 " dbh in 1/10 acre plots and trees < 4.5 " dbh in 1/100 acre plots. Therefore to convert to t C/ha values per tree mass is multiplied by 24.71 for trees > 4.5 " dbh and by 247.1 for trees < 4.5 " dbh (1 hectare = 2.471 acres).

Table 2.2. The allometric regression equations of Jenkins et al. (2003) and the Blodgett Forest species to which they are applied

	Equation group	*Representative species*	*Regression equation*	*R^2*
Softwood	Cedar/larch	Incense cedar, Giant sequoia	Biomass (kg) = exp(-2.0336 + 2.2592 ln.*dbh*	0.98
	Douglas-fir	Douglas fir	Bm (kg) = Exp(-2.2304 + 2.4435 ln.*dbh*	0.99
	True fir/hemlock	White fir, Pacific yew, Nutmeg	Bm (kg) = Exp(-2.5384 + 2.4814 ln.*dbh*	0.99
	Pine	Ponderosa pine, Sugar pine, Lodgepole pine	Bm (kg) = Exp(-2.5356 + 2.4349 ln.*dbh*	0.99
Hardwood	Mixed Hardwood	Chinquapin, Dogwood, Tanoak, Madrone	Bm (kg) = Exp(-2.4800 + 2.4835 ln.*dbh*	0.98
	Aspen / alder / cottonwood / willow	Alder spp.	Bm (kg) = Exp(-2.2094 + 2.3867 ln.*dbh*	0.95
	Hard maple / oak / hickory / beech	Black oak, Live oak, Maple spp.	Bm (kg) = Exp(-2.0127 + 2.4342 ln.*dbh*	0.99

2.2.1.2. Belowground biomass

Belowground carbon biomass can be added using the formula of Cairns et al. (1997), which is able to predict root biomass regardless of latitude, climate and edaphic conditions:

Root Biomass Density (t/ha) = exp[-1.085 + 0.925 ln(aboveground biomass density)] $r^2 = 0.83$

2.2.1.3. Litter and duff

The depth of litter and duff are measured as part of the Blodgett forest permanent plot methods. The BFRS plots measure the depth of litter and duff separately. This division has little meaning for biomass estimation and so the two were combined for all measurements and analyses discussed here. In order to produce a correlation with carbon biomass, measurements were taken of depth and mass and subsamples were collected to determine dry weights. A strong relationship ($n = 31$, $r^2 = 0.91$) was obtained between depth and carbon biomass (Figure 2.4):

Litter/duff carbon biomass (t C/ha) = 5.4887x + 3.7141

where x = depth of litter/duff in cm

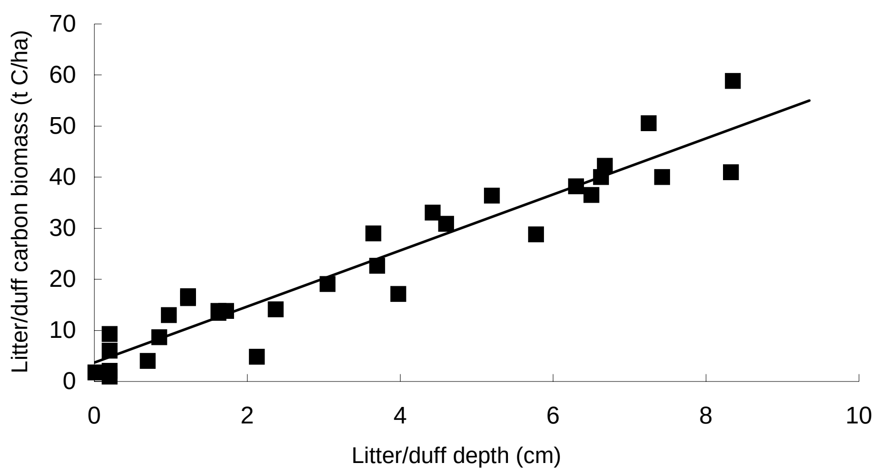


Figure 2.4. Relationship between Litter/Duff Depth and Carbon Biomass

This relationship could then be applied to the BFRS permanent plot data to determine any relationships between forest age and litter biomass, or aboveground biomass and litter biomass.

2.2.1.4. Dead wood

Dead wood in the BFRS permanent plots is measured along two 37.2 feet lines. Dead wood with a diameter of > 3 inches is measured along the whole length of the lines, wood between 1 and 3 inches is measured along 10 ′ and wood < 1 inch diameter is measured along 6 ′ of each line. The line intersect method (Brown, 1974, Harmon and Sexton 1996) determines the volume of wood per hectare from the diameters of the pieces of wood that cross a line of a given length.

Volume (m^3/ha) = π^2 * [($d1^2$ + $d2^2$…….dn^2)/8L]

where d1, d2 etc = diameters of intersecting pieces of dead wood and L = length of the line.

The BFRS crews measure dead wood in five decomposition classes. Winrock International experience has shown that five classes are too fine scale to have meaning with regard to biomass and so the five classes were combined into three coarser and consequently less ambiguous decomposition classes: sound, intermediate and rotten.

Blodgett Class A	=	Sound
Blodgett Classes B and C	=	Intermediate
Blodgett Classes D and E	=	Rotten

In the BFRS plots no decomposition class is given to dead wood of < 3 inches and so here arbitrarily all dead wood of this size is given the intermediate class.

To determine biomass from calculated volume the wood density at each decomposition stage is required. Winrock collected 26 samples across the three decomposition classes. The derived densities (Table 2.3) were used with the BFRS permanent plot data to create a relationship between forest age and lying dead wood carbon biomass.

Table 2.3. Oven-dried dead wood densities measured by Winrock in October 2003

Density Class	*Density (Mg/m^3)*	*95 % CI*
Sound	0.50	0.10
Intermediate	0.32	0.09
Rotten	0.17	0.06

Dead wood also can be found in the form of snags or standing dead wood. This also is measured in the Blodgett Forest permanent plots. The biomass of these trees can be calculated identically to the calculations for live trees with a subsequent deduction for the decomposition /degradation status of the tree. As standing dead wood forms a relatively minor biomass component, for the sake of simplifying calculations we arbitrarily use a limiting factor of 0.8 here to account for fallen needles, leaves, twigs and branches and in some cases tops.

2.2.1.5. Soil carbon

Soil samples were collected at seven sites to estimate the carbon content to 30 cm depth. The sites represent a recently logged forest—4 years after logging, 13 years after logging, and an old-growth site. After the litter and duff had been removed, a composite sample of 3 standard soil cores were collected for carbon measurements and one standard soil core for bulk density. The carbon content was measured by a commercial laboratory using the dry oxidation method.

Soil carbon is estimated as, in t C/ha: bulk density (g/cm^3) x depth (cm) x percent carbon (%).

No corrections were needed for stones rock, fragments etc.

2.2.2. Modeling growth on the without project case: even-aged management

2.2.2.1. Aboveground live biomass

Blodgett forest was logged heavily early in the 20th century and commercial clearcut logging was subsequently not restarted until volumes had recovered in the 1960s. As a consequence the forests in Blodgett are aged either between 70 and 100 years old or less than 40 years old, and there exists a missing section of data for any chronosequence calculations. This hole was filled using a tree growth model. The model used by Winrock is the Chapman-Richards growth model (Richards 1959, Pienaar and Turnbull 1973). The model was fitted as closely as possible to the Blodgett data to allow estimation of biomass for forests of any age (Figure 2.5). One compartment has no record of any harvest activity. Here arbitrarily the age of 200 years is given to this piece of forest to represent an age at which most facets of the forest should have reached maturity.

Model scenarios included the following assumptions: (1) all species considered together by defining average growth and shade tolerance among species, (2) absence of fire, and (3) no effect of reduced yields in successive harvests.

Confidence intervals of 95% for estimated biomass carbon density were calculated as per Sokal and Rohlf (2003); referencing residual standard deviation between observed and predicted values.

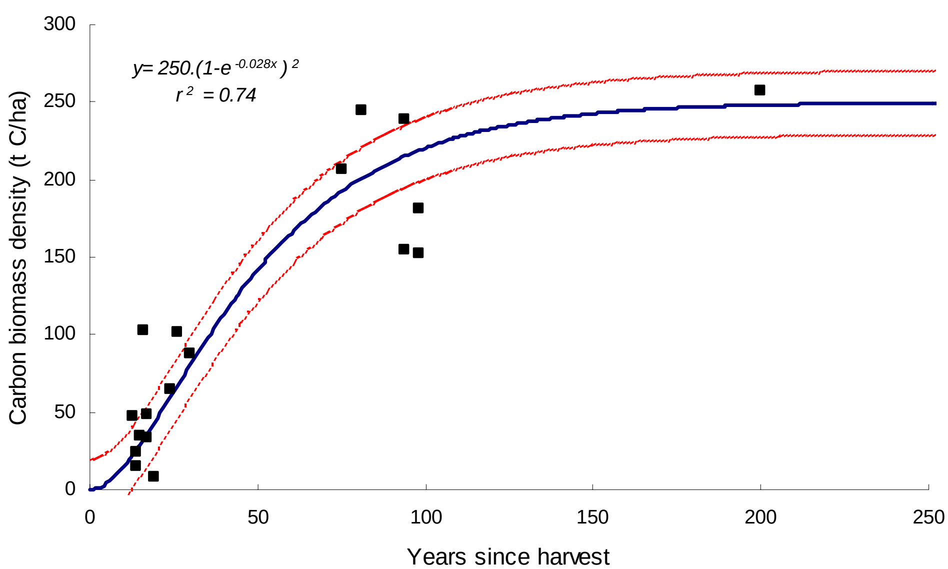


Figure 2.5. The Blodgett plot data fitted to a Chapman-Richards growth curve (± 95 % CI)

In the absence of clearcut harvest and/or catastrophic disturbance, these even-aged stands are likely to become uneven-aged over time. At BFRS stand reinitiation appears to start after approximately 100 years (R. York, personal communication); this process will gradually lead to an uneven aged condition.

2.2.2.2. Forest floor and dead wood

Biomass of litter and lying dead wood in the BFRS permanent plots were most closely related to compartment ages. In figures 2.6 and 2.7 plot data for litter and dead wood respectively are plotted against compartment age. A regression curve was fitted to the data to allow a prediction of carbon biomass from age:

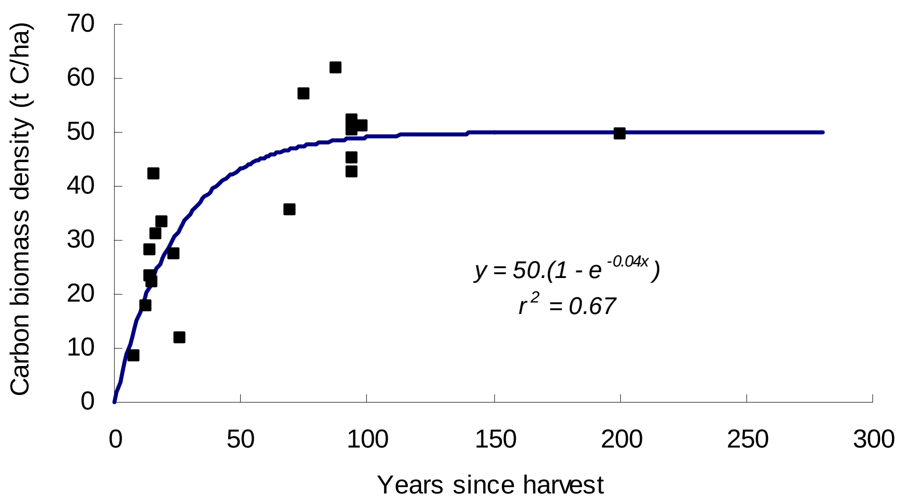


Figure 2.6. Relationship between forest age and carbon biomass of litter and duff

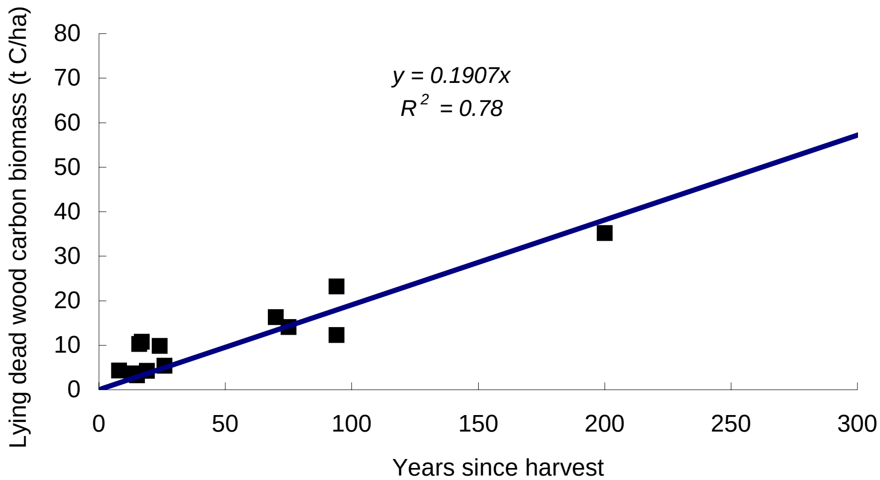


Figure 2.7. The relationship between forest age and carbon biomass of down dead wood

The litter layer can become a significant carbon pool especially under conifer species and in dry ecosystems such as exist at Blodgett. In the absence of fire biomass accumulates steadily in this pool. Other authors have measured up to 100 Mg/ha in pinyon/juniper or 123 Mg/ha in ponderosa pine of a similar age to the older forests in this study (Tiedemann,1987, Covington and Sackett, 1992). The value for ponderosa pine compares favorably with the maximum value of 124 Mg/ha calculated from the Blodgett dataset.

Standing dead wood correlated strongest with aboveground biomass. In Figure 2.8 the relationship between live aboveground biomass carbon density and the carbon density in standing dead trees is illustrated.

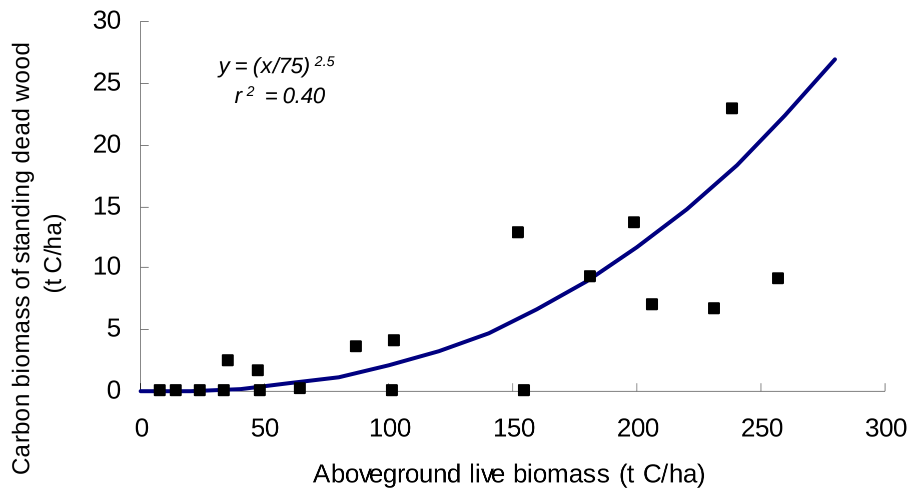


Figure 2.8 The relationship between aboveground live carbon biomass density and carbon biomass of standing dead wood

2.2.2.3. Soil organic carbon

The soil measurements taken by Winrock International show a slight elevation in the amount of soil carbon in the 4-year-old compartments as opposed to the approximately 100-year-old compartments (analysis of variance with Tukey's test for pairwise comparison of means). The cause is probably the input of carbon matter following the slash-burning fires. However, the significance of this difference disappears within 10 years. Due to this short-term nature and relatively small extent of the effect, changes in soil carbon through time will not be considered in this analysis.

Differences in soil carbon resulting from changes in management are seldom discernible or long-lived. Soil carbon can be reduced slightly immediately following harvest (Laiho et al, 2002, Carter et al, 2002), however, any losses should be rapidly re-assimilated as the succeeding forest regrows with accompanying soil organic matter inputs (Carter et al., 2002). Relative difference in post-harvest effects on soil carbon between varying harvest intensities are slight and often undetectable (Carter et al., 2002). We thus assume that stocks of soil carbon are equal among the with- and with-out project cases and thus do not include this pool in the analysis.

2.2.2.4. Carbon pools summed

In Figure 2.9 the accumulation of biomass in each of the biomass components is modeled through 280 years. It should be noted that in the absence of fire, the dead wood pool continues accumulating biomass after all other pools have greatly diminished their accumulation rates. This is why many scientists consider stocks of dead wood as indicatory of the true maturity of a forest.

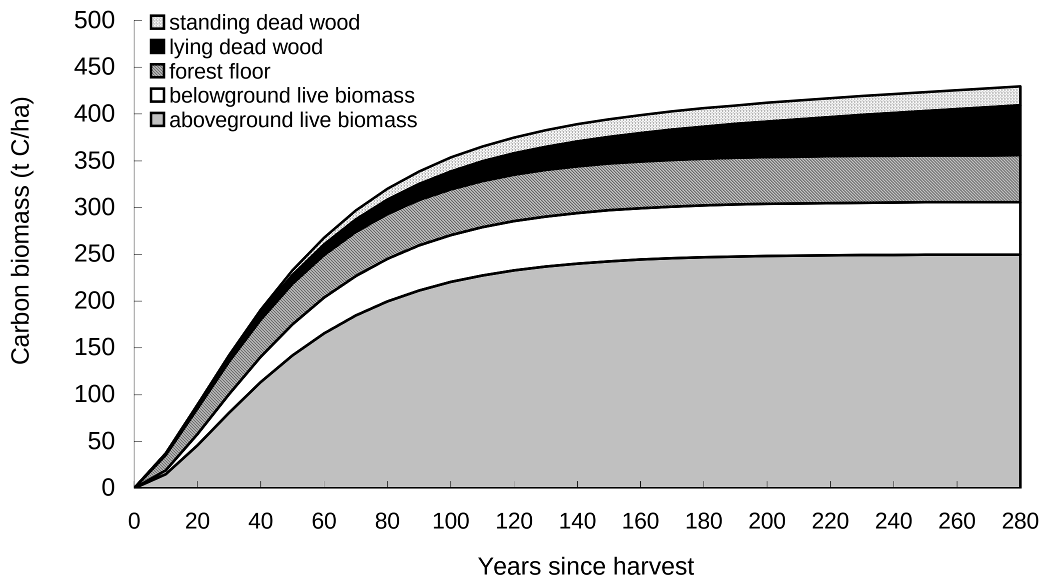


Figure 2.9. Carbon accumulation in a Sierran mixed conifer forest modeled over 280 years

Following all the biomass-component additions it is possible to model the live vegetation over any growth cycle including logging cycles typically applied to Sierran mixed conifers in Californian. In this region, even-aged management with an 80-year rotation is often applied in commercial forestry (Ed Murphy Sierra Pacific, pers. comm.), and once the timber has been extracted, litter, slash and any remaining vegetation is bulldozed into piles (Figure 2.10) and burned leaving virtually no residual biomass pools (personal observation). Modeling the forest cycle permits the long-term average carbon biomass density to be calculated (Figure 2.11). Here we estimate a long-term average over an 80 year rotation of 179.2 t C/ha (excluding derived long term wood products).

Figure 2.10. A slash pile in the forest at Blodgett

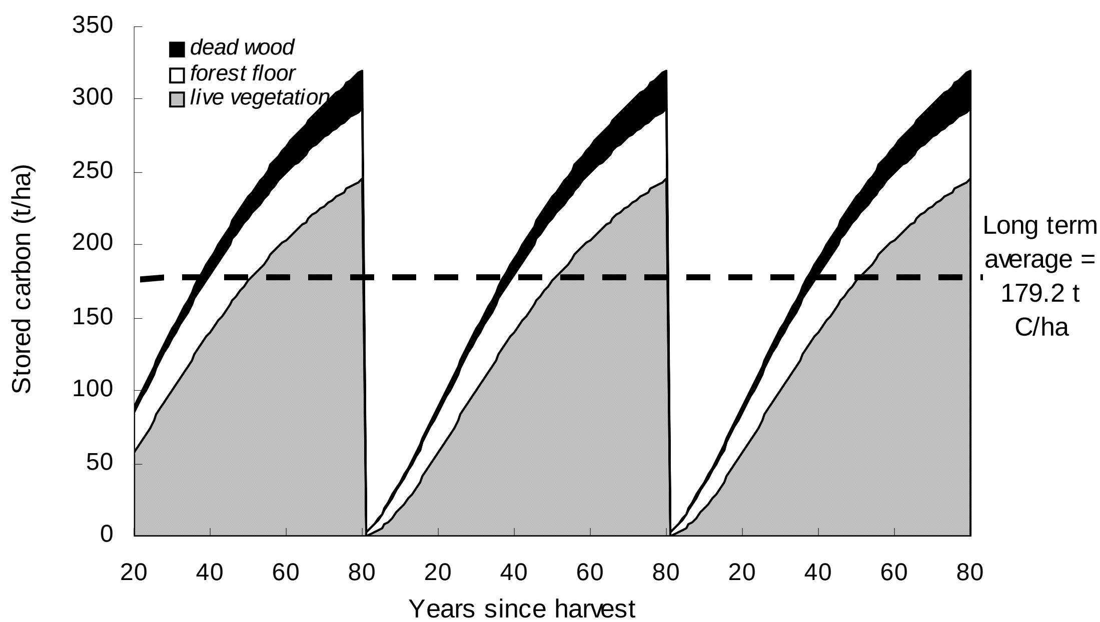


Figure 2.11. Growth and harvest cycles for live biomass in Sierran mixed conifer forests, the long-term average carbon biomass density is indicated

2.2.2.5. Long-term wood products

To any analysis of carbon benefits involving logging, long term wood products (LWPs) must be considered. Timber felled in the forest is not immediately lost as emissions to the atmosphere. A proportion is carried to a processing mill; of this, a proportion is converted into products, and of this, a proportion of these products is destined for long-term use (storage).

Each of these progressions has an efficiency associated with it, which was quantified and used to predict the fate of a typical removal of aboveground biomass via harvest. *Harvest efficiency* (i.e., biomass harvested as a percent of pre-harvest standing biomass) of 43% was used as reported by Birdsey (1996). Logging slash left on the site is assumed to be immediately oxidized as brush piles are burned shortly after harvest. Sawlog *transformation efficiency* conforms with conversion factors employed by Todd Morgan et. al. (unpublished) – 85% harvested stem wood = bole wood (15% bark), and 43% of bole wood converted to sawn wood and veneer (5.2 board feet per cubic foot). The resulting percentage of harvested volume, 37%, conforms closely with the same authors' independent findings based on year 2000 surveys of California mills, where 34% of wood fiber harvested was transformed to finished lumber or plywood/veneer. Relative production of all wood and waste products reported by Morgan et. al. included sizeable streams to co-generation plants (34% of harvest) and pulp and paper (18% of harvest). For simplicity in this analysis, production streams are grouped into two classes: sawn wood and waste streams (Figure 2.12). As the only pulp mill in California sources from outside the Sierra Nevada region, pulp and paper streams were thus not considered in the model. "Waste streams", including wood fiber for co-generation, landscaping material, and animal bedding, were defined based on anticipated short residence time of carbon and are assumed to be oxidized immediately in the model. The proportion of sawn wood products destined for long-term ($\geq$ 5 years) use were specified at 80% for sawn wood, based on findings summarized in Winjum et al. (1998).

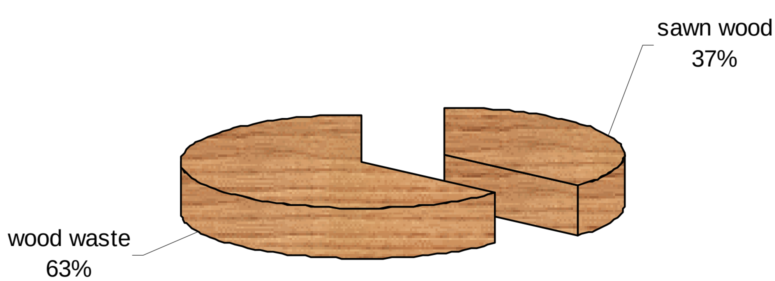
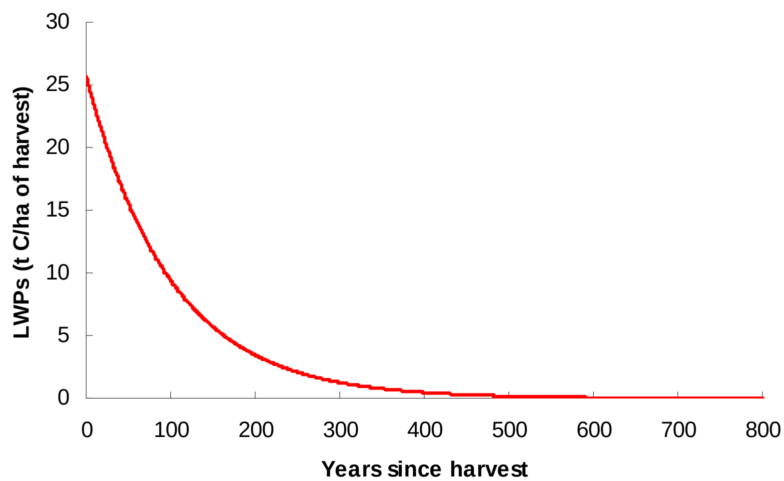


Figure 2.12. Proportions of harvested timber converted to saw and veneer logs and various wood waste streams as reported by Morgan et. al. (unpublished) from Surveys of California Wood Product Plants in 2000

Rates have been calculated for the oxidation of different LWPs through burning or decay. Wood products in long-term use were retired over time using an annual oxidation factor of 0.01 for sawn wood, as reported by Winjum et al. (1998). In Figure 2.13 the "retirement" (i.e., oxidation) of wood products from a Sierran mixed conifer forest is modeled both from a single harvest and from 80 year harvest cycles.

a.



b.

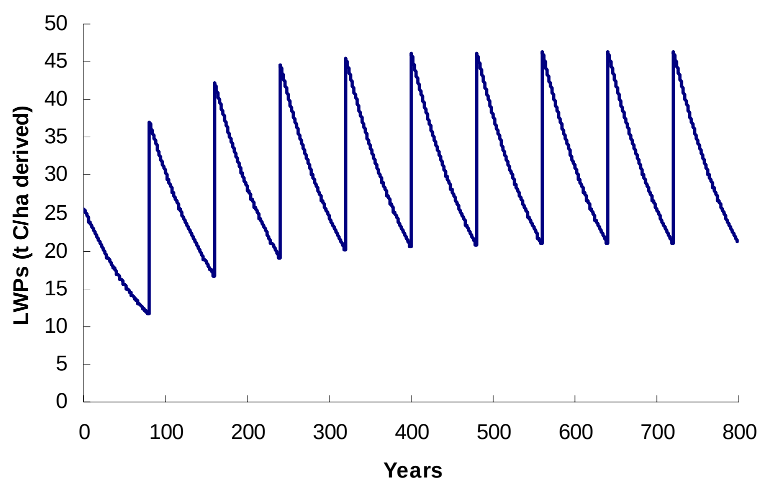


Figure 2.13. The oxidation of long-term wood products through time. (a) After a single harvest, and (b) with multiple harvests on an 80-year rotation

2.3. Change in forest management

2.3.1. Specific growth rates for forest management component in BFRS

2.3.1.1. Group selection regeneration

The group selection growth rate used here is an adaptation of the standard growth rate (calculated in Section 2.2.2). York et al. (2004) show that five years after harvest height is 13.1 % diminished in trees growing in 0.6 ha group selections as opposed to 8 ha clearcuts. A 13.1 % decrease in height and dbh (the relationship between dbh and height is assumed to be broadly linear) leads to a 44.7 % decrease in volume. As volume is directly proportional to biomass the age at which the peak mean annual increment (MAI) is reached was therefore increased by 44.7 % to produce the growth curve for trees regenerating in group selection plots (Figure 2.14). Here carbon biomass is decreased by 44.7 % at five years of age in group selections when compared with clearcuts: annual increment is also assumed to be 44.7 % lower at five years. The difference in annual increment between group selections and clearcuts subsequently decreases in a linear manner until equality is reached at 60 years after harvest when it is assumed that regeneration will have reached canopy height. Maximum and minimum values are calculated by applying the same factors to the confidence intervals deduced for the even-aged growth curve calculated in Section 2.2.2.

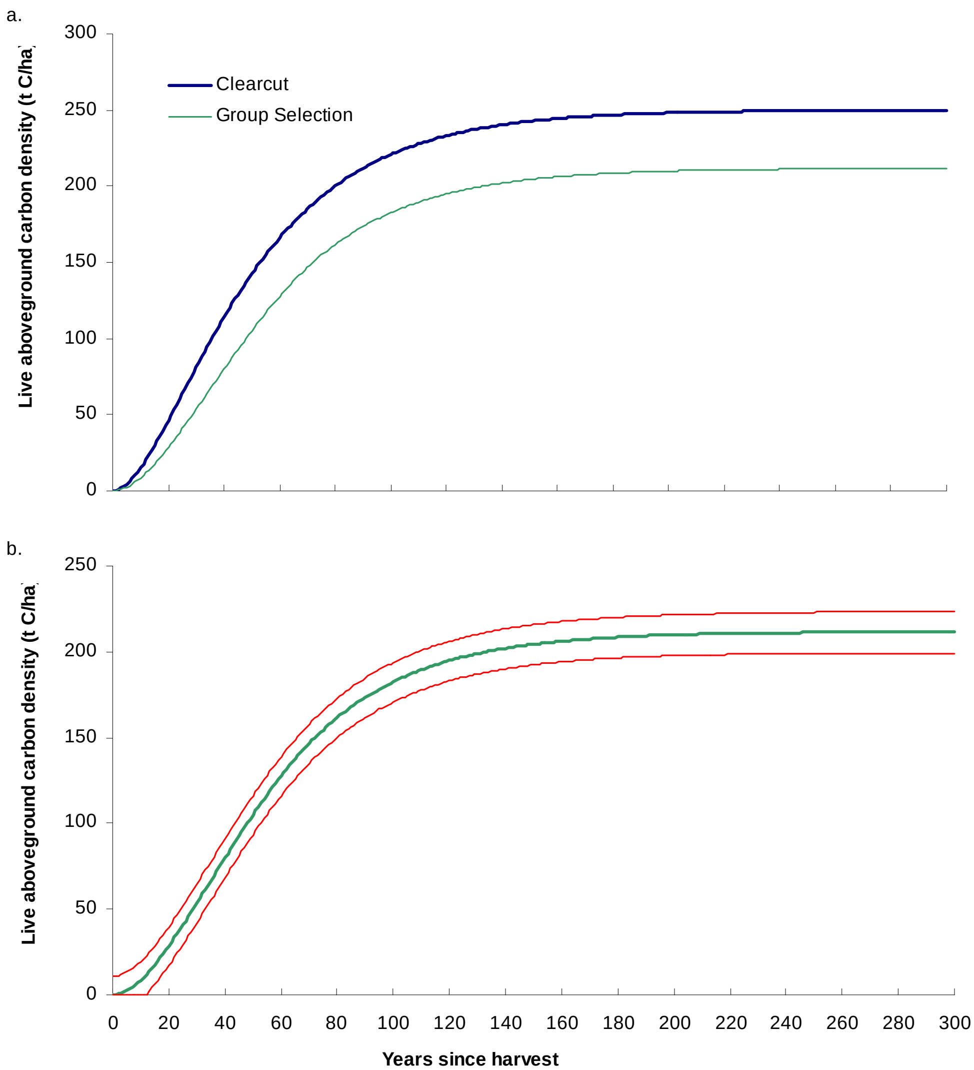


Figure 2.14. Growth curves for trees in regenerating group selections. (A) Group selection trees relative to trees in a clearcut. (B) upper and lower bounds of growth rate for group selection trees

The period of decreased growth rate for the regrowth in the group selections also results in a decrease in the maximum *yield*, as compared with clearcuts (c.f. Figure 2.12), which agrees with observations that "released trees approach, but never reach, the size of those which grew at the post-thinning spacing all along" (Pienaar, 1965, Oliver and Larson, 1996).

2.3.1.2. Group selection border trees

Border trees growth rate is also an adaptation of the standard rate calculated for regeneration growing in regenerating clearcuts. York et al. (2004) measured an average 41 % enhancement in the radial mean annual increment (RMAI) for trees bordering group selection openings relative to trees within the forest five years after harvest. The enhancement was not affected by spatial position around the opening nor by the size of the opening. A 41 % increase in radius (at dbh) is equivalent to an increase in biomass of 125 % (the average of values calculated using the equations of Jenkins et al. [2003] for pines, true firs, Douglas fir and cedar/larch). This factor was applied to the standard curve of annual biomass increment. Here the conservative assumption is made that the growth response peaks at five years of age (the only age evaluated) and then declines in a linear manner until the adjacent regeneration reach canopy height (estimated at 60 years). Confidence intervals are applied to the growth rates by applying the border tree growth enhancement to confidence intervals calculated for the even-aged growth curve calculated in Section 2.2.2.

The period of increased growth rate for the trees bordering the group selection opening also results in an increase in the maximum yield. As well, the magnitude of the growth response varies with the age (vigor) of the stand at the time of release, which is a recognized determinant of the capacity of the residual trees to respond to release. In this study the age of the surrounding forest will be 40, 60 and 80 years old in three separate scenarios. In Figure 2.15 the growth curves of border trees relative to trees not adjacent to a canopy opening is displayed. The effect of the 10 years of growth enhancement, based on the year at which enhancement happened, can be visualized.

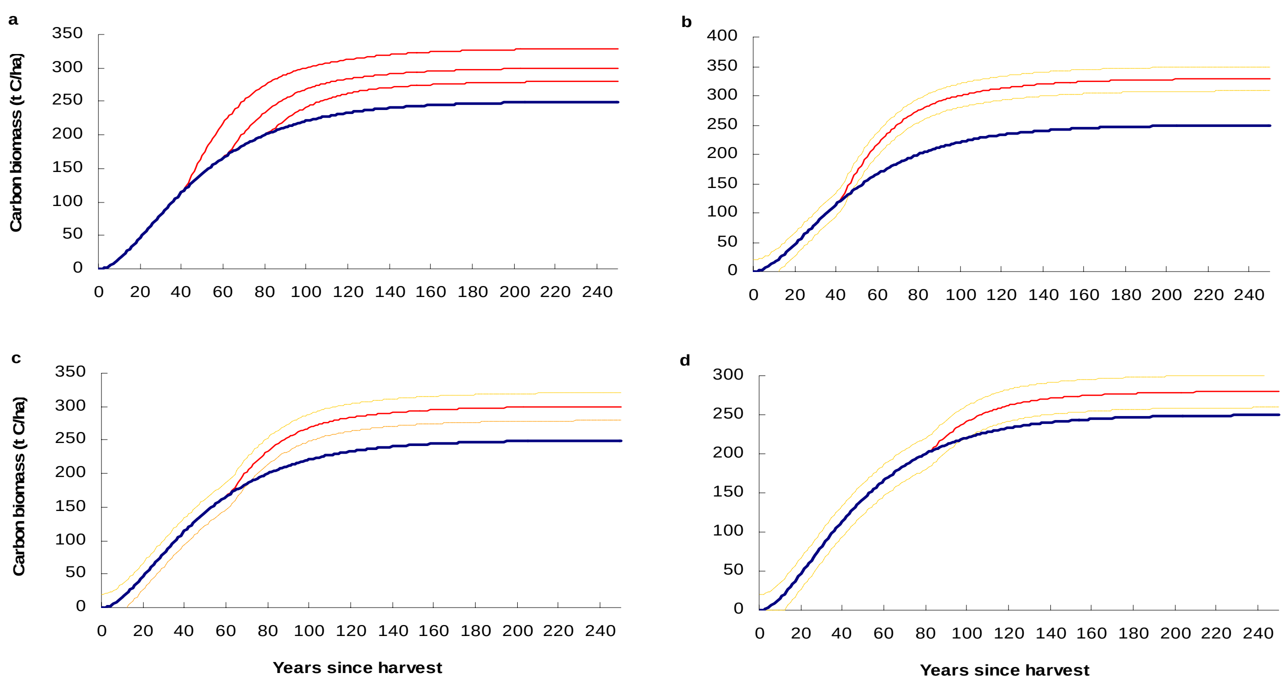


Figure 2.15. Border tree growth rates. (a) Harvests happening when border trees average 40, 60, or 80 Years of Age, (b) harvest when trees average 40 years of age ± 95 % CI, (c) harvest when trees average 60 years of age ± 95 % CI, (d) harvest when trees average 80 years of age ± 95 % CI

2.3.2. Specific model scenarios for the Blodgett case study

2.3.2.1. With-project group selection scenario

The starting condition will be post-harvest with the remaining forest of three ages with separate examination of each initial forest condition. Pools considered included above- and below-ground biomass, litter, and dead wood. Harvest-derived pools like slash and long-term wood products were not considered because they are equal among the with- and without scenarios with equal areas harvested. Matrix forest ages: 40 years old / 60 years old / 80 years old, all growing under even-aged conditions. The model will predict forwards 50 years.

Group Selections:

8 ha harvested and regrowing with the group selection growth rate starting age zero

3.4 ha border trees growing with the border tree growth rate starting age 40, 60, 80

12.5 ha matrix forest growing with the normal growth rate starting age 40, 60, 80

2.3.2.2. Without-project clearcut scenario

The starting condition will be post-harvest with the remaining forest of three ages with separate examination of each initial forest condition. Pools considered included above- and below-ground biomass, litter, and dead wood. Matrix forest ages: 40 years old / 60 years old / 80 years old, all growing under even-aged conditions. The model will predict forwards 50 years.

Clearcut:

8 ha harvested and regrowing with the normal growth rate starting age zero

0.9 ha border trees growing with the border tree growth rate starting age 40, 60, 80

15 ha surrounding forest growing with the normal growth rate starting age 40. 60, 80

2.3.3. Results

In all scenarios the highest carbon benefits lie in the without project scenario. Regardless of initial age more carbon is stored in vegetation after a clearcut rather than in an equal area of group selection harvests. Carbon sequestration is higher (marginally) in the surrounding vegetation (the area not harvested; 15.9 ha / total of 23.9 ha) of the group selection harvests due to the greater area (3.9 X) of the border trees (with their elevated growth rates). However, this is greatly outbalanced by the enhanced sequestration by the regeneration regrowing within the clearcuts in comparison to those within the group selections (Figure 2.16).

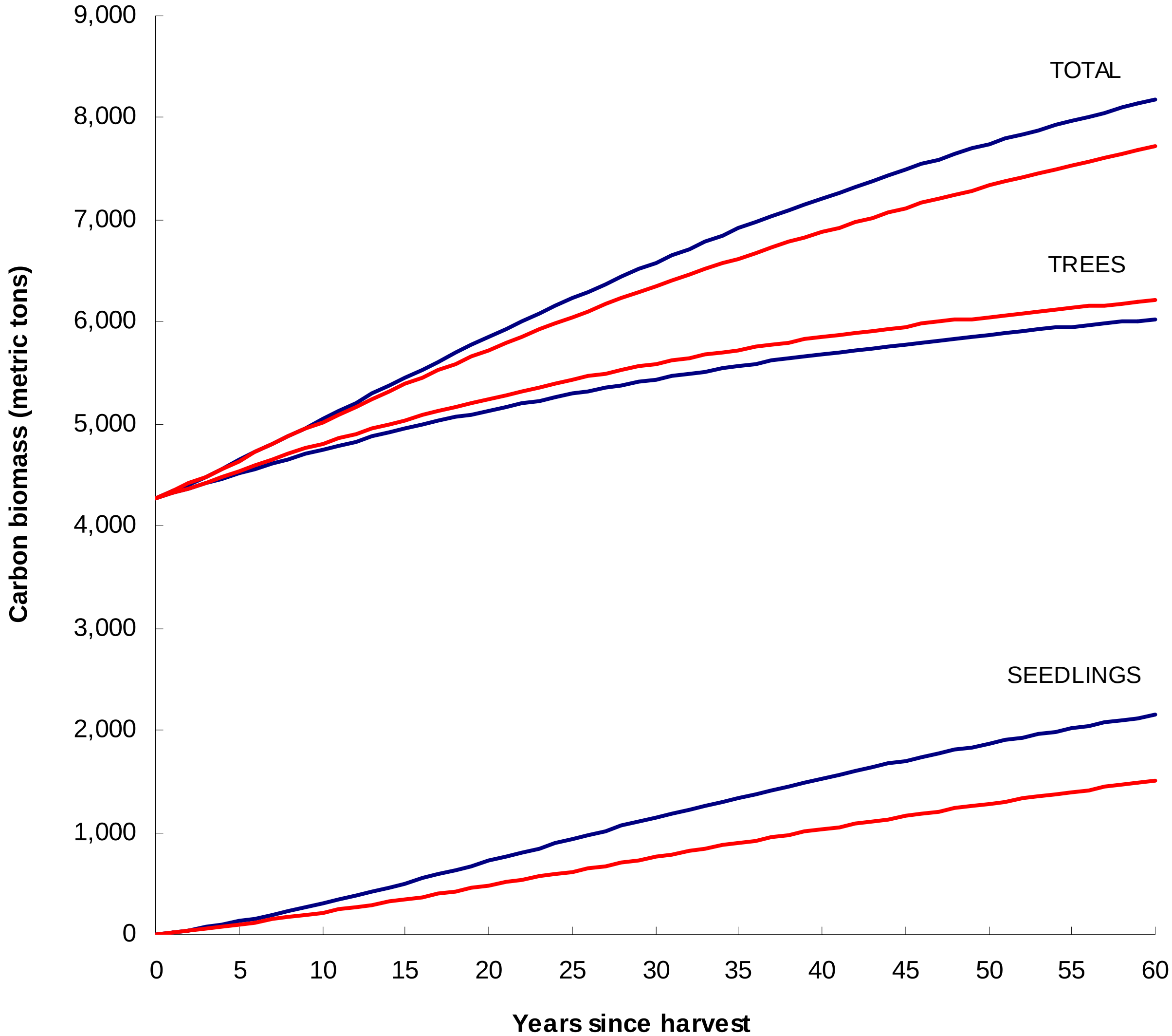


Figure 2.16. Stored carbon in the clearcut (without project) and group selection (with project) scenarios. Here the surrounding vegetation was aged 60 at the time of harvest. Clearcut is in blue, group selection in red. Only the moderate scenario is illustrated.

The age of the surrounding vegetation at the time of harvest has little effect. The minimal effect is higher sequestration in the surrounding vegetation of the group selection plots if the forest is younger at the time of harvest (Figure 2.17). This is because the release of the border trees is strongest in younger trees (see Section 2.3.1.2.).

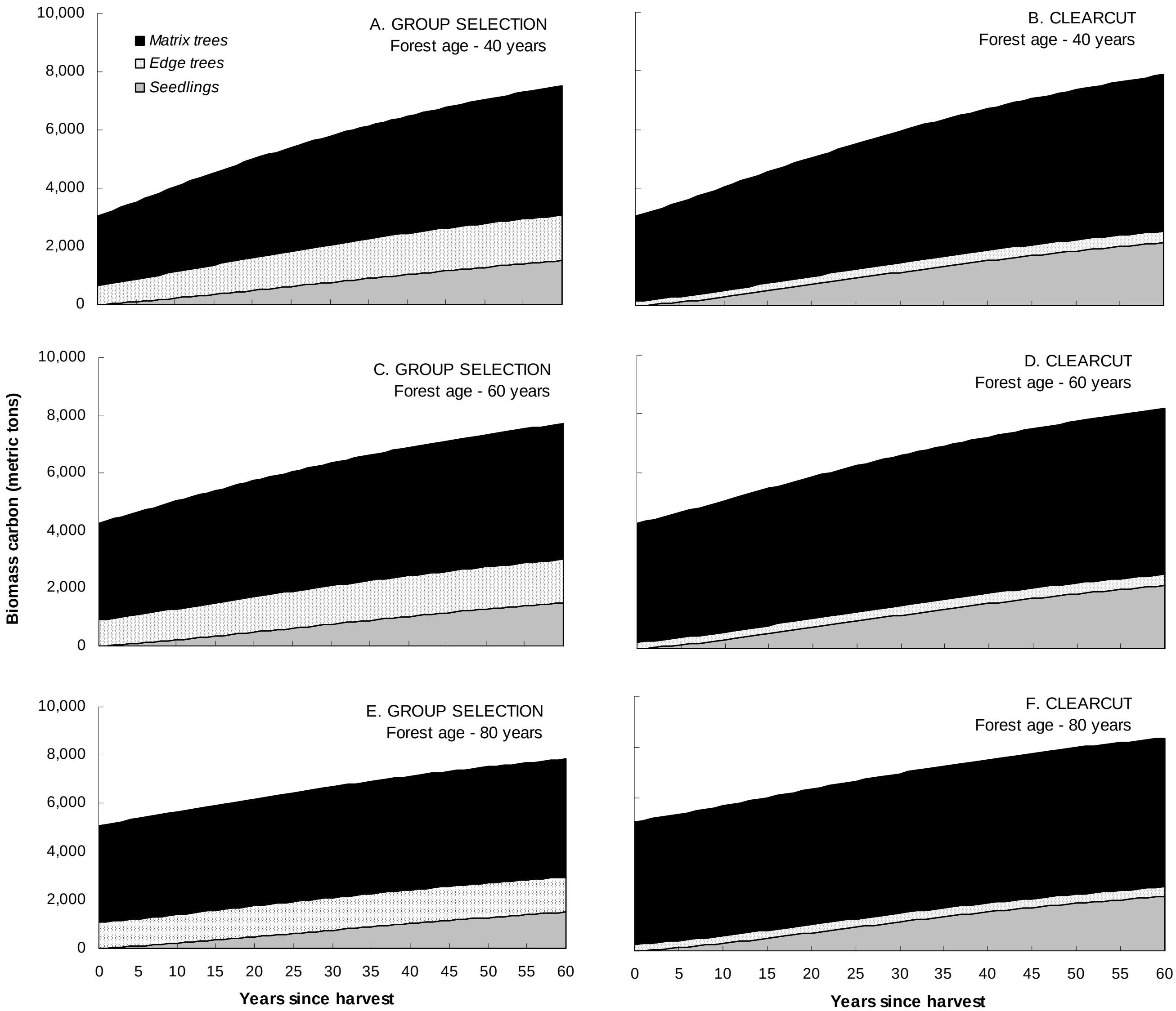


Figure 2.17. Carbon sequestration across harvest treatments and initial ages of the forest. Only the moderate scenario is illustrated. Group selections – 8 ha regeneration, edge trees 3.4 ha, matrix trees 12.5 ha. Clearcuts- 8 ha regeneration, edge trees 0.9 ha, matrix trees 15 ha.

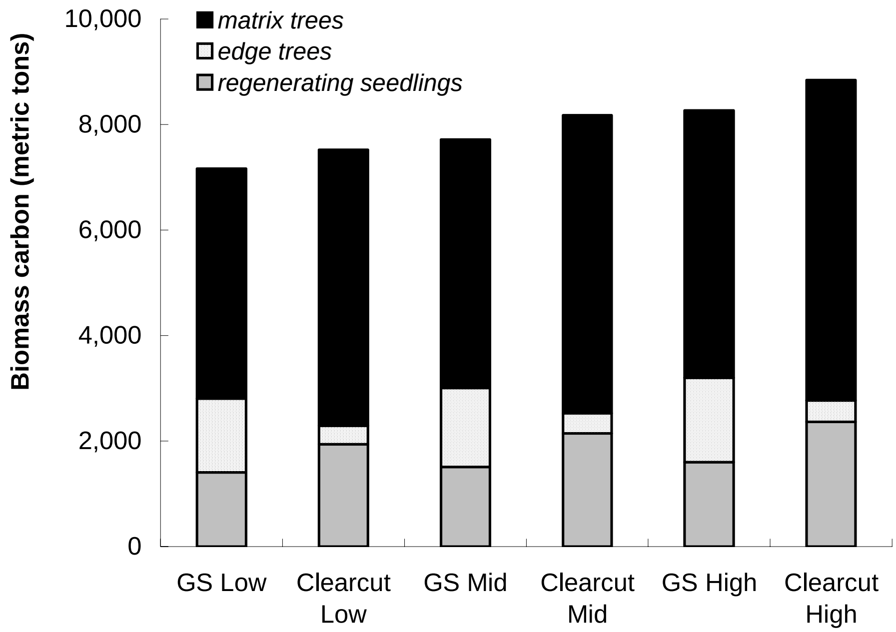


Figure 2.18. Summary of the effects of altering harvest treatment from clearcut to group selection for high, mid, and low scenarios. The carbon sequestration after 60 years in the matrix trees, the edge trees and the regenerating seedlings are illustrated. The age of the forest at the time of harvest was 60 years.

No carbon benefit was therefore found here for switching from clearcut harvests to group selection harvest (Figure 2.18). The advantages may, however, not be just aesthetic and environmental. Here the analysis was on the average of all the commercial species grown at Blodgett. These include both shade-loving and shade-intolerant species. If just the shade-tolerant / shade-requiring species were examined then the benefit of clearcuts for seedling growth might disappear potentially allowing a net carbon benefit from group selection. The study of York et al. (2004) indicates that white fir and Douglas fir could be most suitable for growth in group selections.

White fir regeneration, in particular, were no taller by year five in the 8 ha clearcut (mean height 87 cm) than in the 0.6 ha group selections (mean height 97 cm) of York et al. (2004). Conservatively we can assume that in this circumstance there is no carbon disadvantage in terms of seedling growth and so the border tree advantage will be not be canceled. Over the project area (24 ha) there would be a carbon advantage to group selection harvests after 50 years of approximately 109 t C (4.5 t C/ha) if the surrounding vegetation was 40 years of age at the time of harvest, 73 t C (3 t C/ha) if it was 60 years of age or 45 t C (1.9 t C/ha) if it was 80 years of age. However, it should be noted that white fir is less commercially valuable than ponderosa pine, Douglas fir or incense cedar and the gain from carbon could be voided by the loss in the value of timber.

2.4. Carbon benefits

2.4.1. Forest management – group selection vs. clearcut

No carbon benefit was found for the BFRS area for switching from clearcut to group selection harvests. The trees directly bordering any opening benefit in terms of growth and per unit area there are more of these trees for group selections leading to enhanced sequestration. However, the carbon benefit attained by these trees is outweighed by the higher growth rates and higher carbon sequestration of the regeneration growing in clearcuts as opposed to in-group selections.

The analysis here focused on the average of all commercial species grown at BFRS including both shade tolerant and shade intolerant species. If just the shade tolerant species were the focus then a different outcome could emerge. Species such as white fir and Douglas fir do not grow at a significantly slower rate in 0.6 ha group selections than in clearcuts and there is even evidence for white fir that growth could be faster in the group selections (York et al. 2004). In this case, a net carbon advantage would arise for the change in forest management but this advantage would likely be small - not exceeding 5 t C/ha after 50 years.

The estimates provided here are assessments of the potential carbon benefits from changing harvest management from clearcut to group selection. In this report we have outlined details of the measurements and the types of analyses needed to calculate the with- and without-project carbon stocks when there are existing inventory data and how to consider the variance in calculating the number of plots required for measuring and monitoring (see Appendix 1). Where there are no existing inventory data, additional measurements would be required but the analyses would essentially be the same as those given here. In a separate report we will provide more details on the methodology for collecting the field data.

In addition to the carbon benefits, there are also several economic issues related to group selection cuts that revolve around the costs of harvesting. Larger clear cuts are usually cheapest on a per unit harvested basis due to economies of scale of the operation. Foresters have to spend less time moving equipment from site to site, moving equipment and logs through forested areas, and moving labor from place to place. Further, on some sites that are only suitable for cable yarding, group selection cuts may be particularly costly due to the logistics of setting up cables and choosing locations for the group selection cuts. An economic analysis was performed on the comparison between clear cuts and group selection for a variety of main production forests in CA and as expected the cost were higher for group selection than for clearcuts. For example, on 10% slope group selection was $166-$739/ha higher in cost than clearcuts and on 40% slope the difference was $245-$988/ha higher (see Ch 1 in Volume 2 for details of the analysis).

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3.0 Jackson Demonstration State Forest

3.1. Background information

Jackson Demonstration State Forest (JDSF) is located inland of Fort Bragg in Mendocino County, California. The JDSF comprises more than 50,000 acres of predominantly coastal redwood or coastal redwood/Douglas fir forest. The land was acquired from the Mendocino Lumber Company and the Caspar Lumber Company between 1935 and 1951.

Between 1862 and the 1930's virtually all the old growth comprising the coastal watersheds was cut (see Figure 3.1). The forest now consists of second growth forest aged up to 140 years including very young stands that have been harvested while under state management.

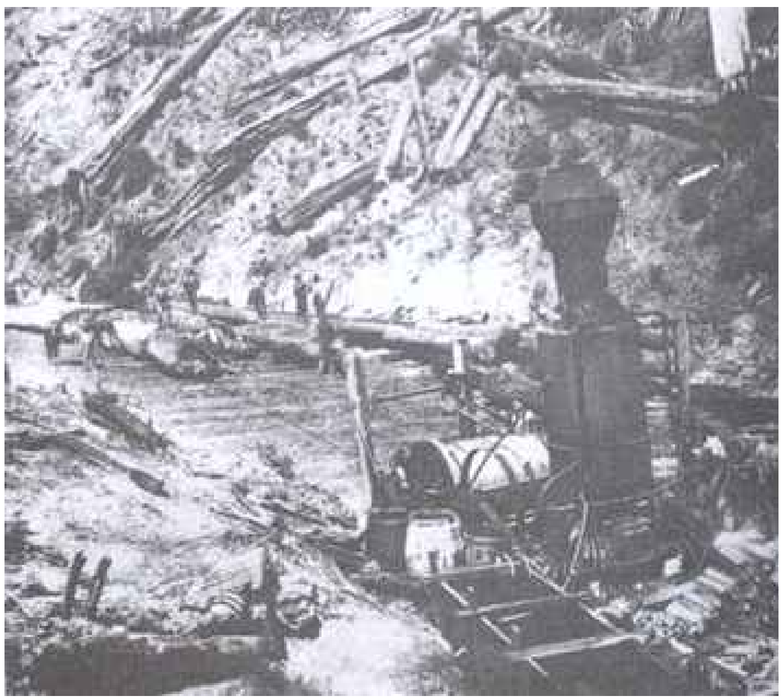

Figure 3.1. Engine and Skid Road Circa 1890, Fort Bragg, California (from Williams, 1989)

The JDSF was established as a demonstration of economical forest management. Its purpose has diversified more recently to include preservation of biodiversity and the fostering of mature forest structure as well as remaining a 'viable and relevant laboratory for resource professionals, private timberland owners, and the general public' (CDF, 2002).

A team from Winrock International visited JDSF in February 2004 to collect data required for biomass estimations. Some of the sites visited are illustrated in Figure 3.2. Measurements were made of trees in and around clearcuts (e.g., Figure 3.3) and group selections and of dead wood, litter, understory and soil carbon.

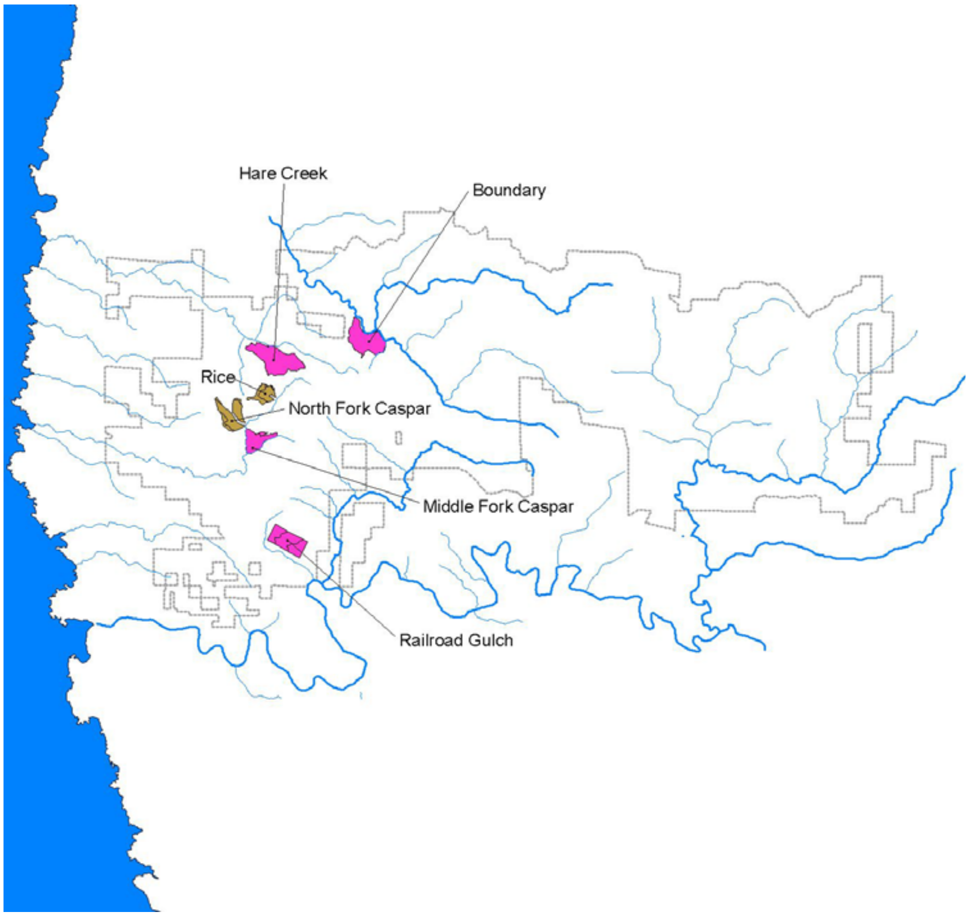

Figure 3.2
Jackson Demonstration State Forest. The location of field investigation sites is indicated: Rice and North Fork Caspar are clearcut sites and the other four are group selection sites.

The tree species commonly encountered at Jackson are listed in Table 3.1.

Table 3.1. The tree species of JSDF. Dominant species are in bold. Commercially grown species are underlined.

Hardwoods	*Conifers*
Tan Oak	<u>**Coastal Redwood**</u>
Pacific Madrone	<u>**Douglas-Fir**</u>
Red Alder	<u>Grand Fir</u>
California Bay	<u>Western Hemlock</u>
Canyon Live Oak	Bishop Pine
Willow	Cypress
Bigleaf Maple	
Eucalyptus	

Figure 3.3. Fifteen-year-old stand of redwood regenerating after a clearcut at JDSF.

3.1.1. Accumulation of carbon on growing redwood stands

Mature redwood stands are famous for their enormous stocks of standing biomass and represent perhaps the most massive forests, per unit area, on earth. Measurements of old-growth (>200 years) redwood stands have yielded standing carbon stocks ranging from 1,650 to 1,784 t C equivalent per ha (Hallin, 1934, Westman and Whittaker, 1975, and Fujimori, 1977). Equally impressive is the rate at which carbon is sequestered in growing redwood stands. A 100 year old redwood stand measured by Olson et al (1990) yielded 3,600 cubic meters per ha, equivalent to 648 t C per ha (at specific gravity 0.36 g oven dry biomass/cm^3 for second-growth redwood (Markwardt and Wilson, 1935)), or a mean annual carbon increment of 6.48 t C per ha per year.

3.2. Biomass calculations for Jackson forest

3.2.1. Aboveground live biomass

There are several sources of data on aspects of the JDSF forest, including the empirical yield tables and data from many infrequent and continuous forest inventory plots. We evaluated these data bases for estimating aboveground biomass and given the various issues with the inventory plots (lack of reliable information on geographic location of the plots and the high variability in age and treatment), we decided to use the yield tables. Estimates of biomass-carbon in other forest components are described below in the corresponding sections. Methods are provided in a separate report (Winrock International 2004) for collecting plot data when existing reliable inventory data do not exist.

The calculations of aboveground live tree biomass presented here are based on the empirical yield tables of Lindquist and Palley (1963). Although 40 years old, these tables are based on empirical data collected in the region and represent redwood growth well (personal communication, Marc Jameson – Forest Manager JDSF). Here the mean DBH (diameter at breast height) and number of trees per acre over 4.5" dbh is used to calculate a biomass-carbon density between 20 and 100 years of age. The DBH is converted to tree biomass using the appropriate formula of Jenkins et al. (2003; Table 3.2; [mass of carbon = 50% dry biomass]).

Table 3.2. The allometric regression equations of Jenkins et al. (2003) and the Jackson Forest Species to which they are applied

	Equation group	*Representative species*	*Regression equation*	*R^2*
Softwood	Cedar/larch	Coastal Redwood, Cypress spp.	Biomass (kg) = exp(-2.0336 + 2.2592 ln.*dbh*	0.98
	Douglas-fir	Douglas fir	Bm (kg) = exp(-2.2304 + 2.4435 ln.*dbh*	0.99
	True fir/hemlock	Grand Fir, Western Hemlock	Bm (kg) = exp(-2.5384 + 2.4814 ln.*dbh*	0.99
	Pine	Bishop Pine	Bm (kg) = exp(-2.5356 + 2.4349 ln.*dbh*	0.99
Hardwood	Mixed Hardwood	Tanoak, Pacific Madrone, Eucalyptus, California Bay	Bm (kg) = exp(-2.4800 + 2.4835 ln.*dbh*	0.98
	Aspen / alder / cottonwood / willow	Alder spp., Willow spp.	Bm (kg) = exp(-2.2094 + 2.3867 ln.*dbh*	0.95
	Hard maple / oak / hickory / beech	Canyon Live oak, Maple spp.	Bm (kg) = exp(-2.0127 + 2.4342 ln.*dbh*	0.99

The site index (height in feet at 100 years) of 160 was chosen as the representative class with 180 and 120 as the upper and lower bounds respectively (CDF, 2002; Shih, 2002; personal communication, Marc Jameson, Forest Manager JDSF).

The biomass yield curves were extrapolated beyond 100 years using first order approximations. The extrapolation was based on plotting an exponential regression curve through the decreasing annualized increase in biomass predicted from the yield tables. In this way the increase in biomass in year 101, 102, 103 etc. could be predicted and added to the total to create a carbon biomass density curve over 250 years (Figure 3.4).

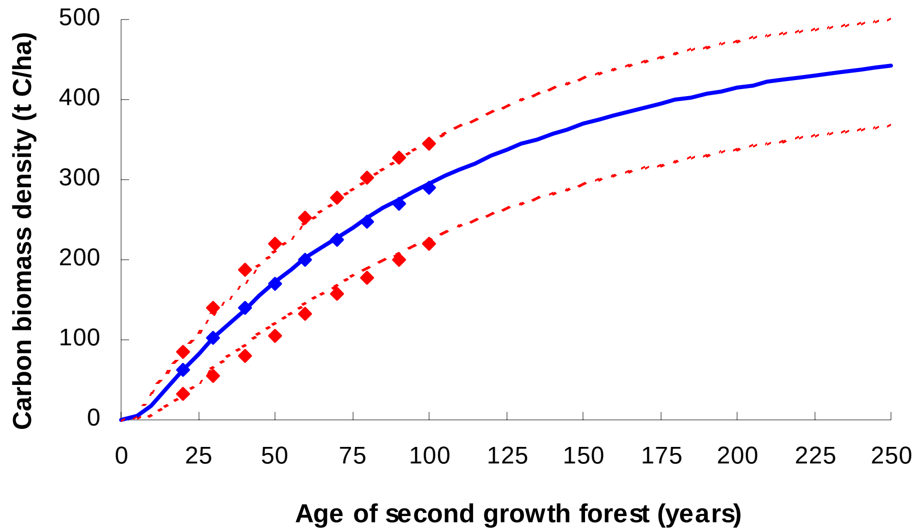

Figure 3.4. Growth curves for redwoods at site indices of 120 (lower curve), 160 (middle curve), and 180 (upper curve). The points represent the results from the yield tables (Lindquist and Pelley, 1963), and the curves are an extrapolation of these points.

3.2.2. Belowground biomass

Belowground carbon biomass can be added using the formula of Cairns et al. (1997), which is able to accurately predict root biomass regardless of hardwood or conifer species, latitude, climate and edaphic conditions:

Root Biomass Density (t/ha) = exp[-1.085 + 0.925 ln(aboveground biomass density)] $r^2 = 0.83$

In the case of JDSF this should be viewed as an underestimation given that new redwood sprouts grow on the root stock of the harvested trees.

3.2.3. Litter and duff

During the February 2004 visit to JDSF, litter stocks were measured at 5 stands (n=28) ranging in age from 14 to ~130 years. Analysis of the measurements generated a model ($R^2 = 0.66$) to describe the accumulation of biomass carbon stocks in litter (Figure 3.5). The form of the model is:

*Carbon biomass density of litter (t C/ha) = 10.4 * (1 - exp(-0.073 * forest age))[4]*

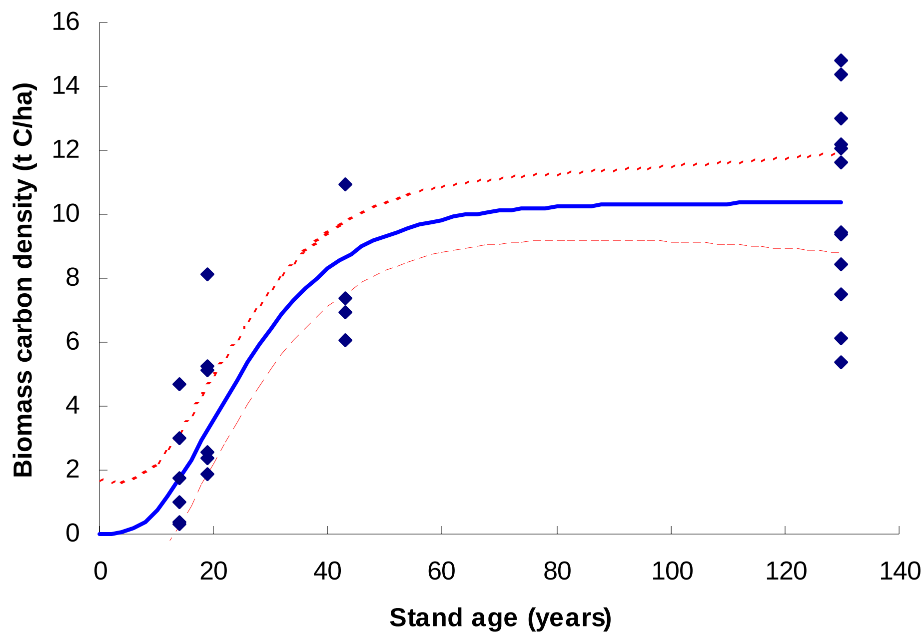

Figure 3.5. Inferred accumulation of biomass carbon in leaf litter on aggrading redwood stands at JDSF with 95% confidence intervals

Leaf litter in older (~130 years) stands averaged 10.4 t C/ha. Pillars and Stuart (1993) demonstrated that mean annual litterfall in mature redwood stands averaged between 1.6 to 2.4 t C equivalent per ha, which must be balanced by equal decomposition to result in the apparently stable stocks of leaf litter noted in mature stands.

3.2.4. Dead wood

Redwood is known for its rot resistance and exhibits very low decomposition rates. Cut stumps and log sections dating from harvest operations conducted over 100 years previous were readily apparent throughout JDSF (Figure 3.6). Studies of downed woody debris in old-growth coastal redwood stands of Mendocino and Humboldt Counties have yielded carbon stocks in downed woody debris ranging from 13 to 100 t per ha (Bingham and Sawyer, 1988, Bingham 1992).

Figure 3.6. Remnant log section from a cut dating from circa 1860–1890

In JDSF as part of the continuous forest inventory (CFI) process, downed dead wood is measured in 141 plots at least every ten years. Logs larger than 7” diameter on the large end are measured in a 26.3’ radius plot and logs larger than 11” on the large end are measured in a 52.7’ radius plot. Logs are only measured where at least one-half of the log lies within the plot boundary. Essentially this method eliminates any accounting for slash left behind after logging, which is generally smaller than the minimum sizes tracked in the JSDF CFI plots. Due to the necessity to select even-aged compartments and the problems with identifying the history of the plots, only 29 plots could be examined across nine different ages. These plots are spread over 50,000 acres and so the spacing is wide, encompassing a wide range of topography, edaphic conditions and species groupings. Consequently wide variation can be expected in what is already an inherently highly variable forest carbon pool (discrete patches of dead trees, created by disturbance, are a defining element in the distribution of dead wood across a landscape).

The down dead wood is classified in one of five decomposition classes (c.f. Maser et al. 1979). Winrock International experience has shown that five classes are too fine scale to have meaning with regard to biomass and so the five classes were combined into three coarser and consequently less ambiguous decomposition classes: sound, intermediate and rotten.

Jackson Class 1	=	Sound
Jackson Classes 2 and 3	=	Intermediate
Jackson Classes 4 and 5	=	Rotten

To determine biomass from calculated volume the wood density at each decomposition stage is required. Winrock collected 30 samples across the three decomposition classes. The derived densities (Table 3.3) were used with the JDSF permanent plot data to create a relationship between forest age and lying dead wood carbon biomass. It is worth noting the close correspondence of the sound density measured here, 0.34 Mg/m³, with known density of redwood, 0.36 Mg/m³ (Markwardt and Wilson, 1935), testament to the dominance of redwood in this forest community.

Table 3.3. Oven-dried dead wood densities measured by Winrock in February 2004

Density Class	*Density (Mg/m³)*	*95 % CI*
Sound	0.34	0.05
Intermediate	0.25	0.03
Rotten	0.16	0.03

In Figure 3.7, the biomass-carbon density of the eligible CFI plots is plotted averaged across the nine age classes, and a regression curve was fitted with an r^2 of 0.79. The wide spread in the data can be expected from the limited number of plots representing a diverse topography with additional variation arising from a range of site indices (edaphic conditions) and a range of species groupings.

The predicted carbon biomass density of 17 t C per hectare at 250 years is within the range reported for old-growth downed dead wood values of between 13 and 100 t C per hectare (Bingham and Sawyer, 1988, Bingham 1992). The highest quantities of dead wood would in fact be expected in old growth redwood stands as only in very mature stands will very large trees die, fall and begin to decompose slowly on the forest floor.

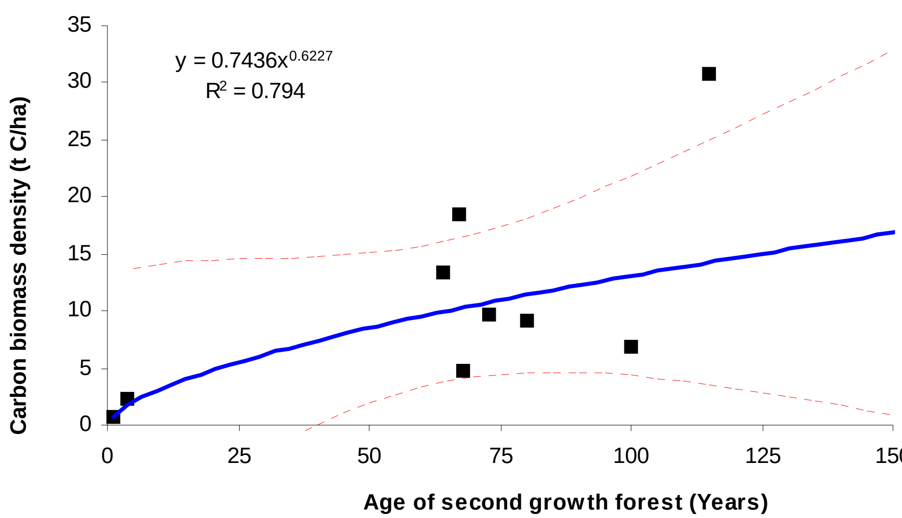

Figure 3.7. Relationship between biomass carbon accumulation in down dead wood and forest age +/- 95 % confidence intervals

Dead wood also can be found in the form of snags or standing dead wood. Although this is also measured in the JSDF CFI plots, it is not considered in the model as a dynamic pool given the difficulty of discerning any accumulation trend (dead wood in forests typically has a short residence time as *standing* dead wood—that is it becomes downed dead wood (Franklin et al, 1996)), as well as the fact that snags are often retained on site to provide wildlife habitat after harvest (thus stands at age zero may have significant standing dead wood stocks).

3.2.5. Understory vegetation

Understory vegetation in the mature stands was mostly dominated by ferns (Figure 3.6). Carbon in understory vegetation samples did not differ appreciably among young (14-19 years) and old (114-144 years) redwood stands. The estimated mean across all of these ages (n=28) was 0.4 t C/ha and was highly variable from site to site (95% C.I. = +/- 0.4 t C/ha), owing in part to the small area (0.1 m^2) of the sample unit. As understory is constant across age classes and represents very little biomass, it will not be included in calculations in this study.

3.2.6. Soil organic carbon

Thirty soil samples were collected from four sites during Winrock's time at JDSF. Each of the samples included measurements of soil carbon and bulk density. The four sites were comprised of two pairs of adjacent young and older growth. No significant differences were noted between the adjacent recently cut (i.e., within the past 14-19 years) and older growth (>114 years) redwood stands (Figure 3.8).

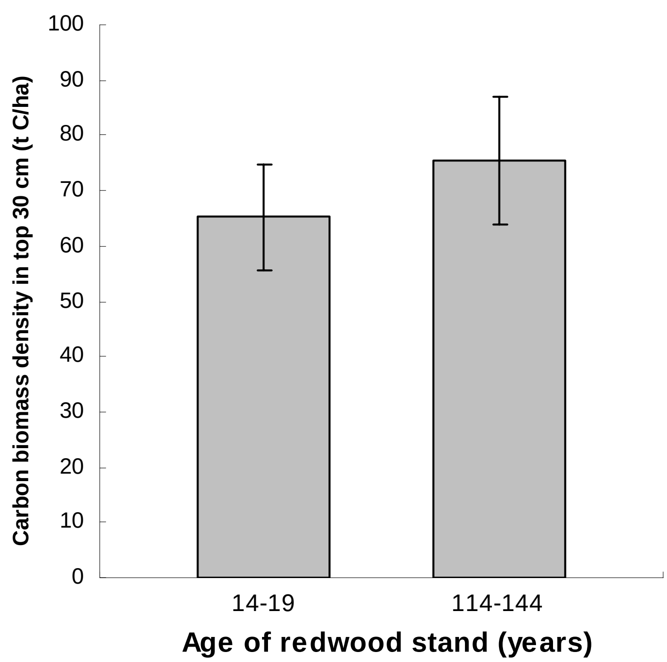

Figure 3.8. Comparative soil carbon in redwood stands harvested 1985/1990 (n=14) and circa 1860-1890 (n=16) at JDSF. Error bars equal 95% confidence interval. Differences are not significant.

Differences in soil carbon resulting from changes in management are seldom discernible or long-lived. Soil carbon can be reduced slightly immediately following harvest (Laiho et al, 2002, Carter et al, 2002), however, any losses should be rapidly re-assimilated as the succeeding forest regrows with accompanying soil organic matter inputs (Carter et al., 2002).

Relative difference in post-harvest effects on soil carbon between varying harvest intensities are slight and often undetectable (Carter et al., 2002). We thus assume that stocks of soil carbon are equal among the clearcut and group selection treatments and thus we do not include this pool in the analysis.

3.2.7. Harvest efficiency, slash and long-term wood products

To any analysis of carbon benefits involving logging, slash and long term wood products (LWPs) must be added. Timber felled in the forest is not immediately lost as emissions to the atmosphere. A proportion is left on site to decompose as slash and a proportion is carried to a processing mill; of this second proportion a further proportion is converted into products, and a proportion of these products is destined for long term use (storage).

Harvest efficiency (i.e., biomass harvested as a percent of pre-harvest standing biomass) was determined as the percent stem volume to a 6 inch diameter inside the bark, following standard commercial limits, using the stem taper function and bark ratio and taper functions derived by Krumland and Wensel (1978). Volumes were determined for ≤ 20 foot log sections of a 90 year old, rotation age, redwood stem of mean dimensions for site index 160 (24.1 inches dbh and 152 feet total height) using Smalian's formula, and volume of the top section was calculated assuming the shape of a paraboloid cone. The top (remaining) section, equal to 1% aboveground stem volume (diameter inside bark equals 6 inches at 129 feet total height), is left on the site as logging slash. We thus assume that 99% (100% - 1% top section) of aboveground stem volume (> 1 foot height) is extracted in a typical harvest operation. As dry mass per unit volume is constant, allocations of volume among components are equally reflective of allocations of mass.

Branch and stem (wood and bark) components, as a percentage of total aboveground biomass, were estimated at 16% and 79%, respectively, as per biomass component ratios developed by Jenkins et al (2003), referencing the mean 90 year old redwood stem described above. Harvest efficiency is thus 78% of aboveground biomass (79% stem * 99% merchantable portion). Slash or woody debris remaining thus equals 17% of aboveground biomass (16% branches + (1% top section * 79% stem))[1]. Much of harvest slash is smaller than the 7" minimum diameter recorded for down dead wood in CFI plots (Figure 3.9), and thus is unaccounted for in the accumulation curve for downed, and coarse, dead wood, but it is included in the model of carbon stock change. Decomposition of slash is modeled at a rate of 0.05 yr^{-1} (Harmon et al., 1987).

1 The remaining ~5% of aboveground biomass is foliage, oxidized immediately in the model.

Figure 3.9. Logging slash on a 15-year-old group selection at the boundary stand, JDSF

The transformation efficiency of receiving mills (e.g., relative output sawtimber, chips, bark, sawdust) was substantiated via interviews with local operators including Mendocino Redwood Company, Simpson Timber Company, Pacific Lumber Company, Willits Redwood Company, and Redwood Empire (Figure 3.10). Reported production quantities were standardized to dry metric tons, assuming specific gravity (dry mass/green volume) = 0.36 g/cm^3, dry weight = 50% green weight, chips and bark reported volumes (i.e., cubic yards) assume 25% airspace, and sawdust reported volumes assume 5% airspace.

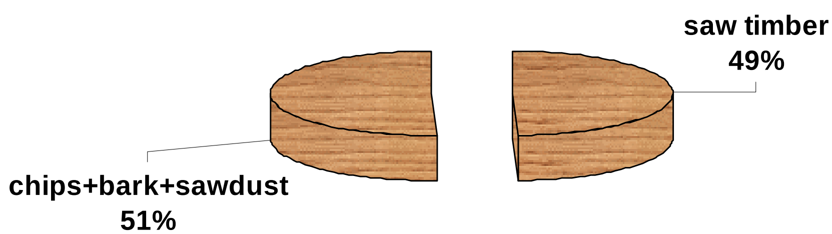

Figure 3.10. Mean proportions of harvested redwood saw logs converted to boards and "waste" streams derived from interviews with northern California sawmill operators (n = 5)

Most of the sawtimber is destined for local/domestic consumption, primarily for use in decking, fencing, and other outdoor lumber products. Chips, which represent 20 to 29% of product streams, are sold as landscaping material, and to a smaller degree are used in co-generation and paper pulp production. With only a single pulp mill operating in the region (and statewide), a small portion of chips are captured by the pulp market. Pulp and paper streams were thus deemed insignificant at the region level and are ignored in the model. Bark, representing 16 to 23% of saw log output, is used for landscaping material and as "hog fuel" in co-generation. Sawdust and shavings, making up 7 to 24% of output, are likewise used primarily for landscaping, and to a lesser extent in fiber-board production. Given the anticipated short residence time of carbon in chips, bark, and sawdust used as landscaping material, their primary end use, these pools, like biomass used in co-generation, are assumed to be oxidized immediately in the model. The proportion of sawtimber products destined for long-term (≥ 5 years) use were specified at 80% for sawtimber, based on findings in Winjum et al. (1998).

Wood products in long-term use were "retired" (i.e., oxidized) over time using an annual oxidation factor of 0.01 for sawtimber products, as reported by Winjum et al. (1998).

3.2.8. Carbon pools summed

The accumulation of carbon biomass over 250 years is modeled for each of the significant carbon biomass pools (Fig. 2.11). At these ages, above- and belowground biomass dominates. Forest floor is much less significant in JSDF than in Blodgett mostly due to differences in climate affecting decomposition rates. Downed dead wood remains a relatively small component even at 250 years of age but it is expected that accumulation would continue for many years after the other pools have stabilized. The largest addition of dead wood will occur when the mature trees die and fall to the forest floor; for redwoods that live for thousands of years these additions of downed dead wood might not occur until 500 years or more have passed. For example, log volumes recorded in stream channels through old growth redwood yielded 2 to 11 times the mass per unit area as from streams through 100-130 year old second growth redwood stands on the north fork of Caspar creek (Napolitano, 1998).

Figure 3.11. Sum of each of the significant biomass density pools for second growth redwood forest accumulating over 250 Years. A site index of 160 and the moderate levels for down dead wood and forest floor are illustrated.

A typical redwood harvesting cycle over three rotations is illustrated in Figure 3.12 including logging slash and long-term wood products and the decomposition of both components. Both logging slash and long-term wood products accumulate through time as the time for complete decomposition exceeds the harvest cycle.

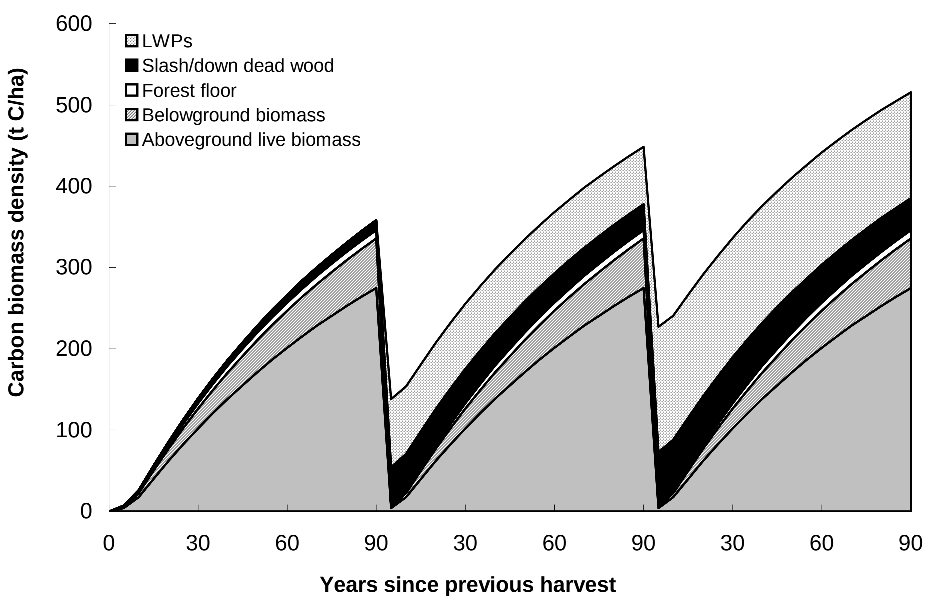

Figure 3.12. Sum of each of the significant biomass carbon pools in and derived from second growth redwood forest (site index of 160) accumulating over three harvest (clearcut) cycles.

3.3. Change in forest management

With conditions defined above, biomass can then be modeled over typical harvesting scenarios. A rotation age of 90 years is used in this analysis, reflecting the mid point between short and long rotations (60 to 120 years) as prescribed in the Jackson Demonstration State Forest Management plan (California Department of Forestry and Fire Protection, 2002), though mean annual increment may not peak until stands exceed 100 years (Noss, 2000).

Despite some evidence suggesting no significant differences in redwood growth among a range of harvest configurations (Helms and Hipkin, 1996), we speculated that redwood regeneration would respond differently to group selections and clearcuts given the appreciable shade-intolerance characteristic of redwood (Olson et al, 1990). In fact, the treatments (uneven-aged silvicultural practices including single tree selection, group selection, and group selection with thinning between the groups) investigated by Helms and Hipkin's (1996) were all characterized by relatively low harvest intensities (post-harvest basal area $\geq$ 38% pre-harvest basal area) and it is possible that the treatments and controls (no harvest) were equally light-limited.

Adams et al (1996) found that individual tree selection resulted in 30-40% slower growth of regenerating and planted redwood stems than in group selection. Similarly, Cole and Helms (1986) remeasured group and individual tree selections at Railroad Gulch in JDSF one year after harvest and found that groups, compared to individual tree selections, fostered not only higher growth rates but also greater sprouting *density*, which would augment the differences in *yields* among different sized harvest units. As natural regeneration of redwood is dominated by sprouts, it is not surprising that sites subjected to heavier cuts, and thus greater density of cut stumps, display greater density of regenerating stems after harvest (Lindquist, 1996). Similar results would be expected comparing group selections with clearcuts, provided that light, or some other resource, continues to be limiting beyond the size of group selections.

Opportunities for changing forest practices exist. Roughly half of forests in the California north coast region are under even-aged management. In 2000 for example, of 21,000 ha of managed forests in the North Coast region, 51 % was under even-aged management, including clearcut, seed tree and shelterwood harvesting, and 27 % was uneven aged management. Of the uneven aged management, only 17 % was under group selection with the remaining 83 % in single tree or cluster selection (California Department of Forestry and Fire Protection statistics).

3.3.1. Specific growth rates for forest management component in JDSF

3.3.1.1. Post harvest regeneration

Nine group selections sites were visited that averaged less than 2.5 ac or 1 ha in area (across four sites) and three clearcuts and measured a total of 928 trees in 32 plots. The group selections represented a range of ages from 6 to 21 years. A wider range of ages would have been preferable, however, the first group selection harvest was only carried out at JDSF in 1983. Plots were randomly located and consisted of a 3 m radius 'small' and an 8 m radius 'large' plot. Measurements of DBH were taken from every tree ≥ 2.5 cm in the 'small' plot and every tree ≥ 5 cm in the 'large' plot. The DBH measurements were converted to biomass using the appropriate equations (listed in Table 3.2) and the biomasses were summed and extrapolated to per hectare densities (Figure 3.13).

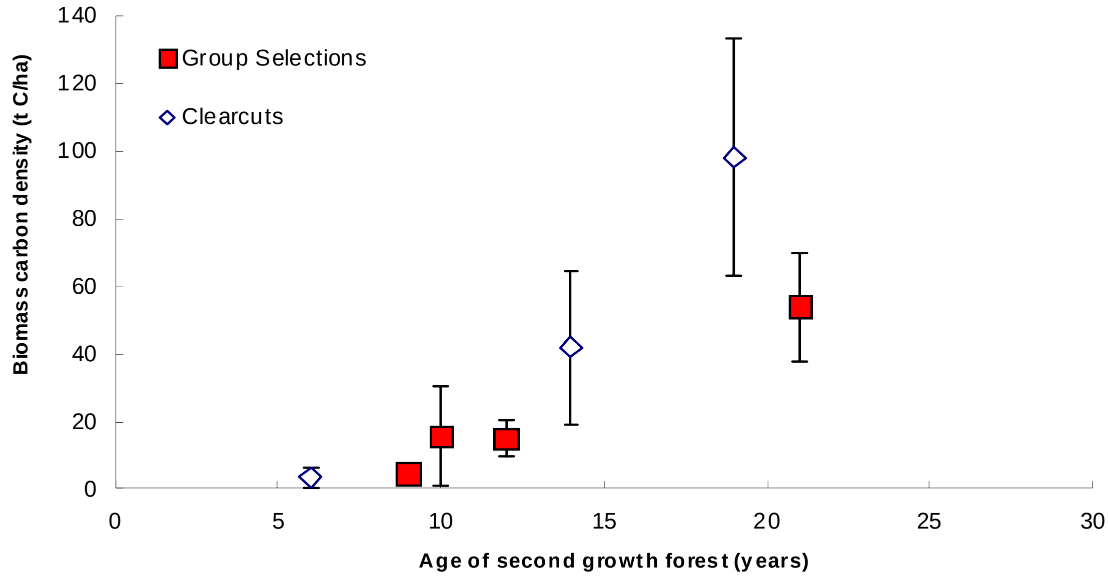

Figure 3.13. Mean (+/- 95 % confidence interval) biomass carbon densities for three clearcut sites (15 total plots) and four group selection sites (9 group selections, n=17).

There appears to be a difference in growth rates between clearcut and group selection sites in each year between the first and twentieth after harvest (Figure 3.13). As no data were collected for older sites, the difference in annual growth rates could not be reliably extrapolated beyond year 20. We assume that the difference in annual growth rates diminishes beyond this point. Lindquist (1996) documented that residual overstory continues to limit growth of regeneration well after harvest (e.g., between years 15 and 20 years post-harvest, periodic increment in mean diameter at breast height was 1.5 times higher on sites with 50 % less residual overstory), but that differences in light conditions steadily deteriorate over time as the residual canopy expands into crown openings. Thus, our assumption is conservative and may underestimate potential differences among the two harvest practices.

The model simulations, prepared for each of three base site indices (120, 160, and 180 feet at 100 years), assumes that the period of decreased growth rate extends through the time required for the regrowth to attain equal height of the adjoining edge trees (46m or 152 feet or 90 years for site index 160 (Lindquist and Palley, 1963)) (Figure 3.14).

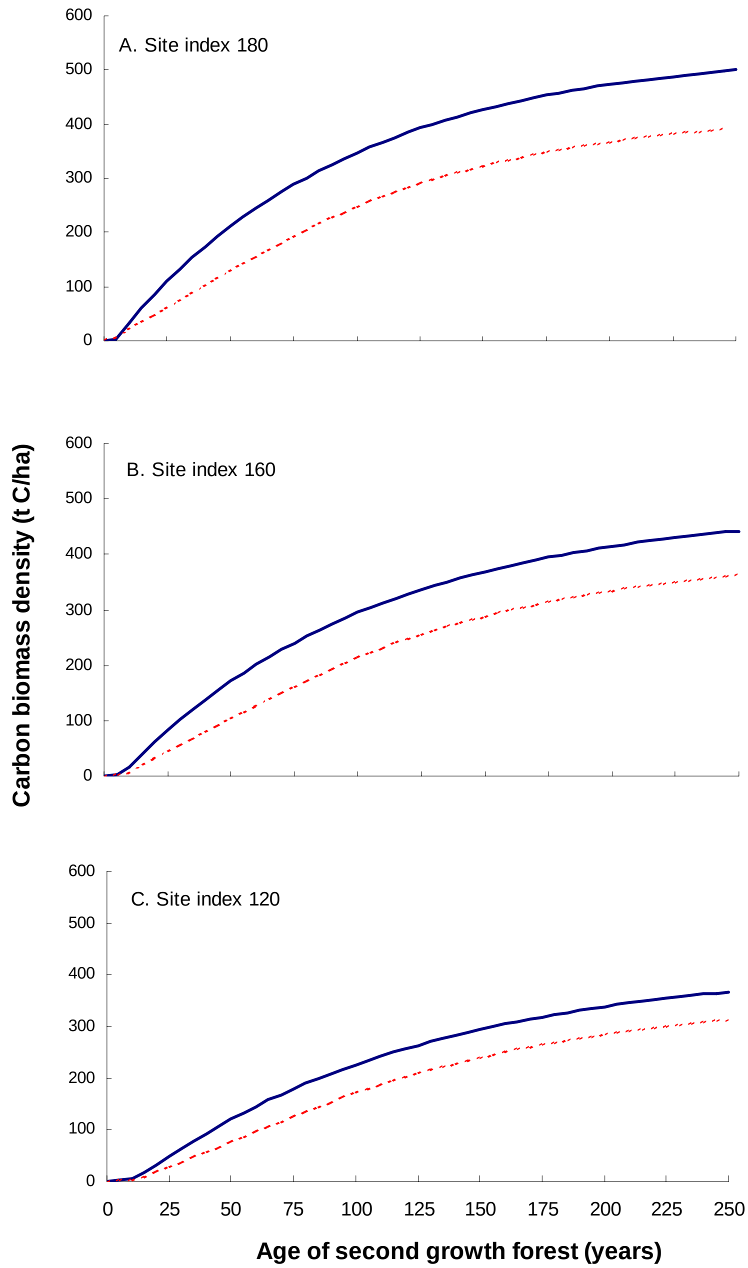

Figure 3.14. Predicted growth curves for second growth redwood stands in clearcuts (solid) and group selections (dotted) at three different site indices 180, 160, and 120. Scenarios predict an impact of the surrounding canopy lasting 90 years (until the seedlings have reached canopy height).

The period of decreased growth rate for the regrowth in the group selections also results in a decrease in the maximum yield, as compared with clearcuts (c.f. Figure 3.14), which agrees with observations that “released trees approach, but never reach, the size of those which grew at the post-thinning spacing all along” (Pienaar, 1965, Oliver and Larson, 1996).

Edge Effects

A further pilot investigation was conducted to assess edge effects on the growth of redwood sprouts. Transects were laid out bisecting two group selections along two axes (N-S and E-W). The two group selections measured in this way were located at the Boundary site, harvested in 1995 (i.e., stocks measured represent 9 years of growth), and were of similar area (0.97 and 0.94 ha). Edge trees measured from 39 to 58 meters in height. Group 1 featured a west-facing slope and Group 2 a north-facing slope. Two nested transects were employed: the wide transect of 5 meters width in which all redwood stems $\geq$ 5 cm dbh were recorded, and the narrow transect of 1 meter width in which all redwood stems < 5 cm dbh (and > 1.3 meters height) were recorded. For analysis, the two transects were integrated by scaling up the 1 m transect to 5 m equivalent (i.e., each stem representing 5 equivalent stems), thus allowing for comparable accounting of all redwood stems > 1.3 meters height. Even after scaling up the small stems recorded in the narrow transect, histograms of dbh class versus frequency approached normal distribution. Mean, maximum, and minimum dbh were calculated for stems located in 40-meter intervals out from the edge of interest.

Given the limited sampling of this peripheral investigation, results are intended for illustrative purposes only. We surmise that light is the principle limiting resource in regenerating redwood stands at JDSF, and that reductions in growth documented here for group selections, as compared with clearcuts, result from a larger portion of the post-harvest gap being influenced by shading from edge trees. Regardless of aspect, shading should be most pronounced at the southern edge of any forest gap (Figure 3.15). No consistent differences in redwood dbh were discerned along E-W transects.

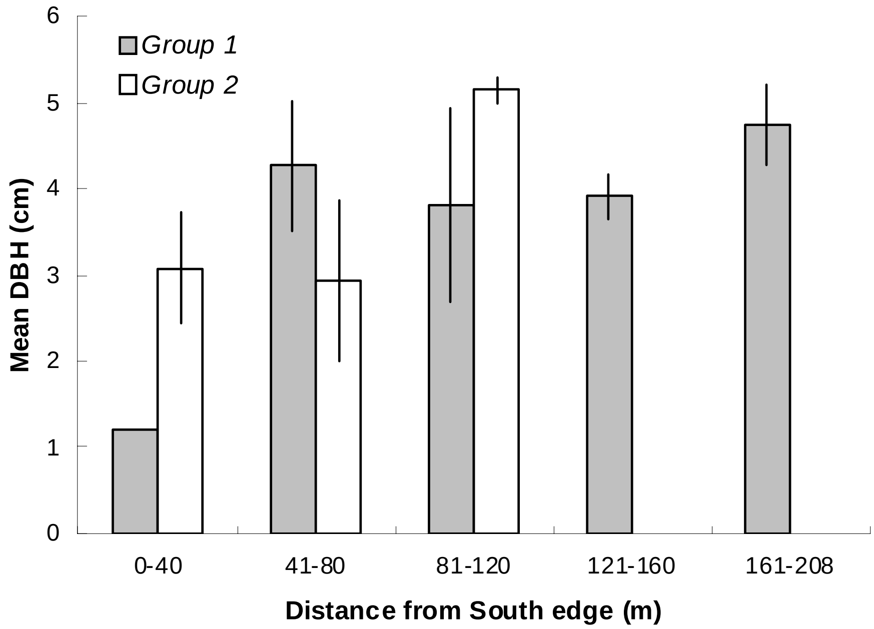

Figure 3.15. Mean DBH (error bars equal one standard error) of redwood sprouts measured along N-S transects in two 9-year-old group selections. Group 1 transect length = 207.5 m, Group 2 transect length = 118 m. No error bars are visible for the group 1 0-40 m interval because the sample is based on measurements (two) of equal magnitude

3.3.1.2. Border trees

Following harvest, light conditions are dramatically improved for trees remaining on the edge of the cut. These edge trees often respond with increased diameter growth (York et al, 2004). Such a response is particularly to be expected among shade-intolerant species, for example coastal redwood. To assess the relative growth response of edge trees, increment cores were obtained from 37 trees on the edge of group selections at 4 sites (Boundary, Railroad Gulch, Middle Fork Caspar, and Hare Creek) and 18 trees from within the forest matrix nearby the same sites. Of these cores, 17 were taken from Douglas fir and 38 from redwood. For edge trees, orientation relative to the gap center (N, S, E, W) was recorded. Trees were selected systematically along transects through interior forest and circumscribing the edge of groups. Cores were taken predominately from the side of the trunk facing the gap, where response in radial increment was predicted to be most readily discernible. Extrapolation to diameter and biomass increment is thus presented as the upper bound of potential response.

Cores were mounted and sanded. Periodic radial increment (mm) was measured for the interval 5 years prior to the harvest date, and in 5-year intervals subsequent to the harvest date. Measurements revealed a distinct ramping up of radial increment on edge trees following harvest (Figure 3.16, Figure 3.17).

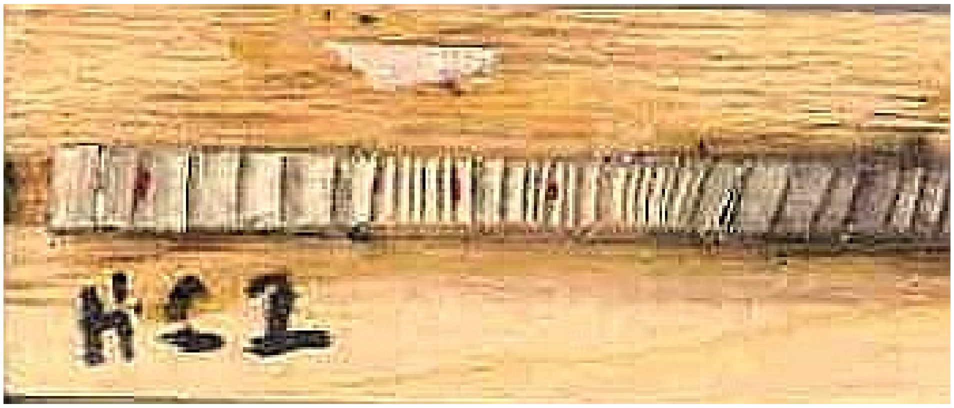

Figure 3.16. Core from standing redwood on edge of Hare Creek group selection. Group selection harvested in 1992.

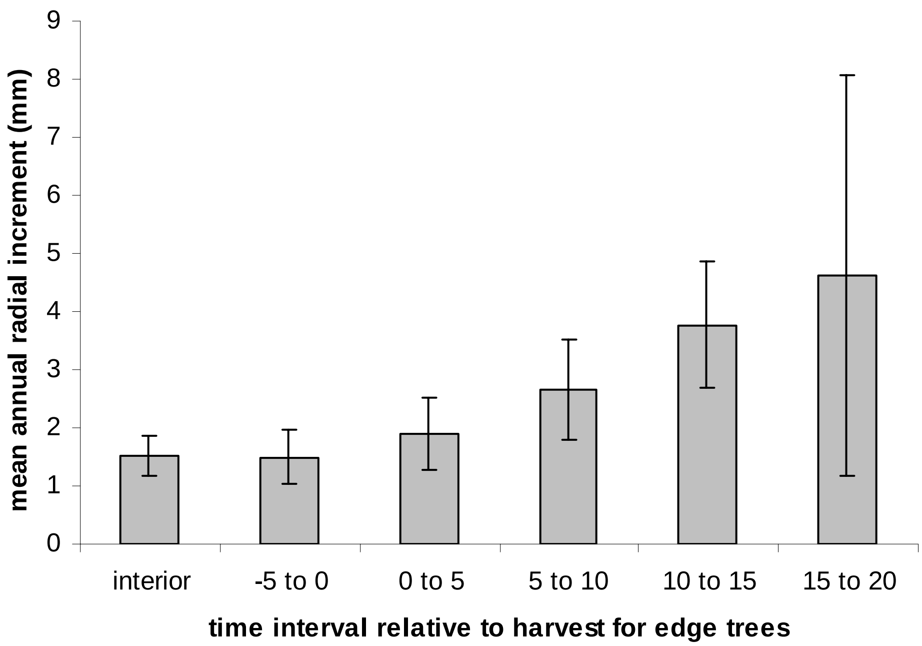

Figure 3.17. Mean annual radial increment for redwood interior trees (n=12) and for edge trees from time intervals –5 to 0 years (n=26), 0 to 5 years (n=26), 5 to 10 years (n=26), 10 to 15 years (n=19), and 15 to 20 years (n=5) relative to harvest. Error bars = 95% confidence interval.

To be certain that the increase noted was not due to year-specific conditions (e.g., rainfall), change in radial increment was compared among edge and interior trees for identical years. As the harvest dates differed among sites (Boundary harvested in 1989, Railroad Gulch harvested in 1983, Middle Fork Caspar harvested in 1994, and Hare Creek harvested in 1992), time intervals relative to harvest did not reflect the same years from one site to the next. Thus, analyses comparing growth response among edge and interior trees were done separately for each site.

For each core, percent changes in mean periodic radial increments relative to mean increment prior to the harvest date (i.e., relative growth response) were calculated as:

5 year periodic post harvest radial increment / pre harvest 5 year periodic radial increment

(10 year periodic post harvest radial increment / 2) / pre harvest 5 year periodic radial increment

(15 year periodic post harvest radial increment / 3) / pre harvest 5 year periodic radial increment

To meet the assumption of normality, relative growth response values were log-transformed.

At Boundary, which received the most intensive sampling, relative growth response of redwood differed significantly (general linear model ANOVA, df = 1, F = 10.23, P = 0.005) among edge trees, mean = 1.70 (95% C.I. = +/- 0.51, n = 14), and interior trees, mean = 0.86 (95% C.I. = +/- 0.26, n=6), for the 15 year interval following the harvest date. Assuming similar pre harvest periodic radial increment, mean periodic radial increment of edge trees was thus 98% (95% confidence range = 6% to 268%) greater than that of interior trees for the 15-year post-harvest interval. At the same site, significant differences among edge and interior trees were not detected for the 5 and 10 year intervals following harvest, which may reflect a lag time in radial increment dependent on prior crown expansion; however, edge trees at Middle Fork Caspar, despite limited sampling (n=3 each for edge and interior trees), showed significant positive relative growth response in the first 5 (P = 0.001) and 10 year intervals (P = 0.017) after harvest.

Jameson and Reuter (unpublished) found an increase in mean annual basal area increment of redwood “leave” trees retained within cutting units, in JDSF from 0.86 % in the four years prior to cutting to 2.54 % in the four years after cutting, equivalent to a relative growth response of 2.93 in periodic radial increment. The leave trees have gained potentially twice the “new” photosynthetically active area as the edge trees under discussion here, which averaged 1.70 in relative growth response.

Orientation relative to the gap center was not found to be a significant predictor of the magnitude of the relative growth response for redwood. For Douglas fir, edge trees showed no significant relative growth response compared with interior trees.

These results were used to model the response of edge redwood trees following harvest. The 98 % comparative response in mean periodic radial increment derived above corresponds with an equivalent 368 % increase (i.e., by a factor of 4.68) in comparative biomass growth (using the equation of Jenkins et al. (2003) for cedar/larch). This factor was applied to the standard curves of annual biomass increment developed for redwood.

For each of three base site indices (120, 160, and 180 feet at 100 years), the period of increased growth rate extended through the time required for the regrowth to attain equal height of the adjoining edge trees (46m or 152 feet or 90 years for site index 160 (Lindquist and Palley, 1963)) and begin producing lateral shade to the edge tree crown. After the first 15 years post harvest, the increase factor for biomass growth rate derived above, 4.68, is progressively diminished according to the exponential function:

$$\text{Increase factor} = 4.68 * 0.908^{\text{(sequential 5 year increment post harvest – 3)}}$$

At 90 years post harvest the increase factor equals 1 and the growth of edge trees resumes at the unadjusted rate of interior matrix trees.

The period of increased growth rate for the trees bordering the group selection opening also results in an increase in the maximum yield (Figure 3.18). In the model, the age of the surrounding forest was set at 90 years. In Figure 3.18, the growth curves of border trees relative to trees in the matrix is displayed.

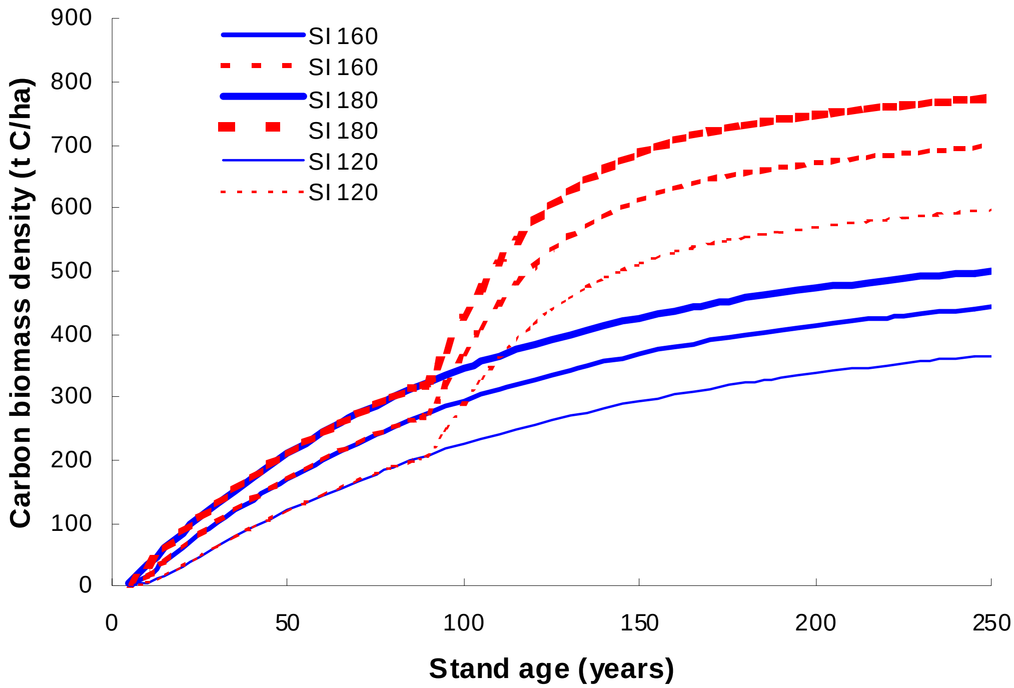

Figure 3.18. Comparative growth of edge trees (dotted lines) and interior matrix trees (solid lines) for a range of site indices. Harvest occurs at age 90.

3.3.2. Specific model scenarios for the Jackson case study

3.3.2.1. Group selection scenario

The model focuses on pure redwood stands on the following site indices: 120, 160, 180. Pools considered included above- and below-ground biomass, litter, and dead wood. Harvest-derived pools like slash and long-term wood products were not considered because they are equal among the with- and without scenarios with equal areas harvested. The starting condition is post-harvest with the remaining forest matrix of age 90 years growing under even-aged conditions. The model predicts forwards for 90 years (i.e., one rotation length).

Group Selections:

8.0 ha harvested and regrowing as per the group selection growth rate

5.6 ha border trees growing as per the border tree growth rate starting age 90

10.3 ha matrix forest growing as per the normal growth rate starting age 90

3.3.2.2. Clearcut scenario

The model focuses on pure redwood stands on the following site indices: 120, 160, 180. Pools considered included above- and below-ground biomass, litter, and dead wood. The starting condition is post-harvest with the remaining forest matrix of age 90 years growing under even-aged conditions. The model predicts forwards for 90 years (i.e., one rotation length).

Clearcut:

8.0 ha harvested and regrowing as per the group selection growth rate

1.4 ha border trees growing as per the border tree growth rate starting age 90

14.5 ha matrix forest growing as per the normal growth rate starting age 90

3.3.3. Results

Over one rotation of the modeled scenarios for JDSF, uneven-aged management with group selections results in slightly increased total forest carbon storage over even-aged management with clearcuts. The advantage is due to the greater (4 X) edge tree response area in the stand under uneven-aged management, as well as the magnitude of the positive edge tree response (60 to 72 % *increase* in yield after 90 years) as compared with the diminished growth of the regeneration within the groups (35 to 50 % *reduction* in yield after 90 years) (Figures 3.19, 3.20 and 3.21).

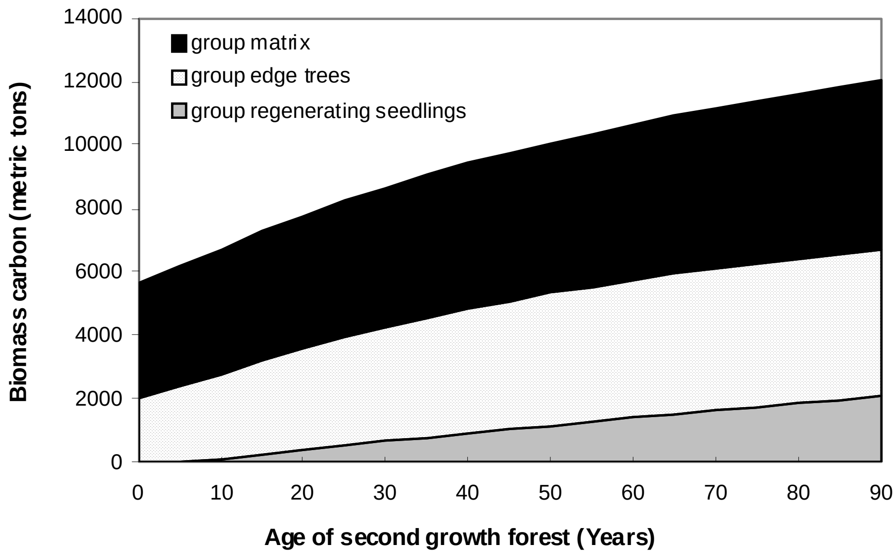

Figure 3.19. Forest carbon storage modeled on the 23.9 hectare redwood stand, site index 160 with moderate levels of down dead wood and litter accumulation, under uneven-aged management with group selections. Regeneration 8 ha, edge trees 5.6 ha, matrix trees 10.3 ha

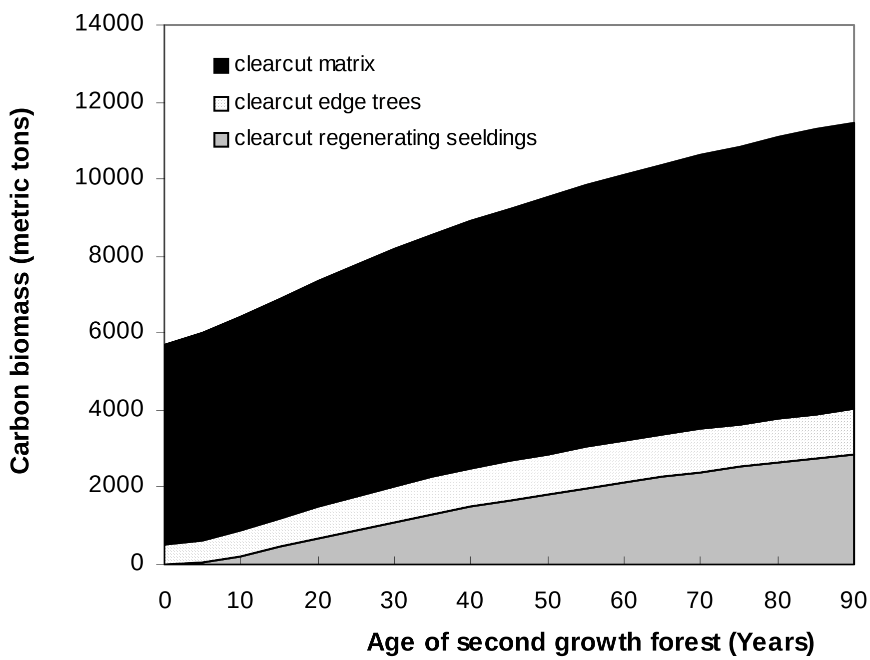

Figure 3.20. Forest carbon storage modeled on the 23.9-hectare redwood stand, site index 160 with moderate levels of down dead wood and litter accumulation, under even-aged management with clearcut. Regeneration – 8 ha, edge trees – 1.4 ha, matrix trees – 14.5 ha.

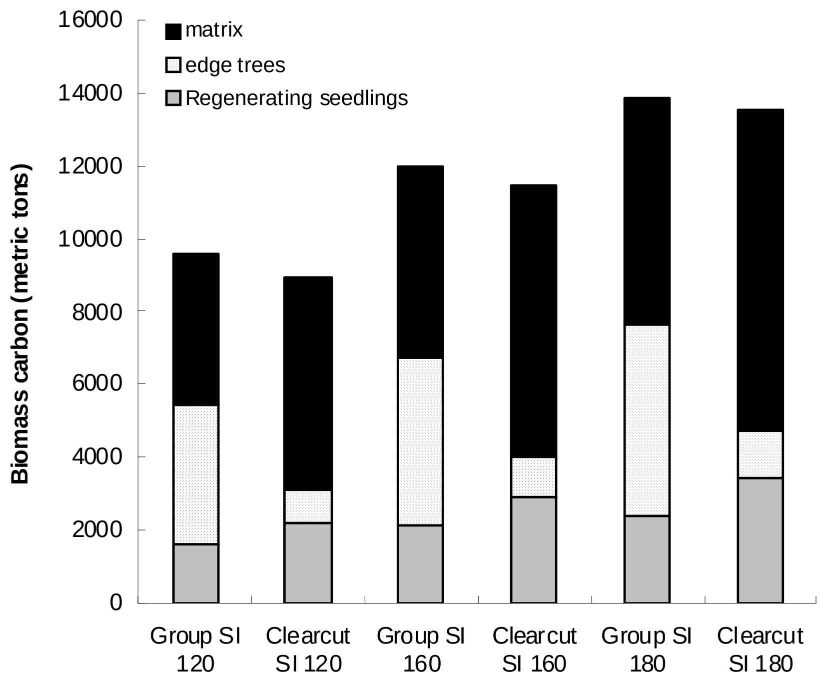

Figure 3.21. Modeled forest carbon storage 90 years after harvest on 23.9-hectare redwood stands under different management for a range of site indices with corresponding levels of down dead wood and litter accumulation

3.4. Carbon benefits

3.4.1. Forest management – group selection vs. clearcut

Over one rotation of the modeled scenarios for JDSF, even-aged management with group selections yielded slight increases, from 337 to 645 tons over 23.9 hectares, in total forest carbon storage over clearcuts (Table 3.4). This is equivalent to an increase in carbon storage per unit area of 14 to 27 tons C per hectare.

Table 3.4. Carbon storage benefits (metric tons) of uneven-aged management with group selections over even-aged management with clearcuts 90 years after harvest on 23.9-hectare redwood stands for a range of site indices (SI) with corresponding levels of down dead wood and litter accumulation.

	Regeneration	Edge trees	Matrix	Total
Group SI 120	1630	3828	4122	9581
Clearcut SI 120	2156	957	5822	8935
			stored C benefit	645
Group SI 160	2090	4632	5280	12002
Clearcut SI 160	2866	1158	7457	11481
			stored C benefit	521
Group SI 180	2371	5277	6231	13880
Clearcut SI 180	3423	1319	8800	13543
			stored C benefit	337

As in the model for BFRS, results are sensitive to (1) the magnitude of the edge tree growth response, (2) the duration of the edge tree growth response, (3) the area of residual forest experiencing edge tree conditions, (4) the magnitude of the growth decrease of regeneration in the group selections, and (5) the duration of the growth decrease of regeneration in the group selections.

Carbon storage advantage of uneven-aged management may be underestimated here, given that the same dbh:biomass function (implicitly: approximately equals specific gravity) was applied to stems growing under different management regimes. The higher wood density widely appreciated in old growth redwood indicates that this species historically (i.e., without management) grew under predominately uneven-aged conditions. The slower growth accompanying this lower light environment results in the denser wood. Wood specific gravity of old growth redwood is 17 % denser than that of second growth (Markwardt and Wilson, 1935, Summitt and Sliker, 1980), which is mostly derived from clearcuts (i.e., growing in even-aged conditions).

The estimates provided here are assessments of the potential carbon benefits from changing harvest management from clearcut to group selection. In this report we have outlined details of the measurements and the types of analyses needed to calculate the with- and without-project carbon stocks when there are existing inventory data and how to consider the variance in calculating the number of plots required for measuring and monitoring (see Section 3). Where there are no existing inventory data additional measurements would be required but the analyses would essentially be the same as those given here (a separate report provides more details on the methodology for collecting the field data; Winrock International, 2004).

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Appendix A

Variance and Number of Plots

A.1 Variance in inventory data

A.1.1 Variance in BFRS plot data

Vegetation

The variance in the plot data is high, however, this is not unexpected given the divergent histories of compartments. Focusing just on compartments aged approximately 80 years:

The coefficient of variation of carbon in live trees = 43 %, based on 47 plots, and the 95 % confidence interval as a proportion of the mean = 12 %

It is suggested that a target for the sampling error be ±7% of the mean, with 95% confidence, so that when additional sources of error are included, the estimated total error will be ±10% of the mean (sampling error usually accounts for more than 80% of the total error; Phillips et al. 2000). The minimum number of plots required to target 7 % sampling error with 95 % confidence = 148. This large number of plots is based on the existing BFRS plots, and points out the need to clearly stratify the area, with strata delineated by carbon stocks rather than other human or biophysical factors.

This is the number of plots that would be required to precisely target the measurement of carbon stocks if similar procedures were followed to those used by BFRS.

A.1.2 Variance in the JSDF plot data

Vegetation

The variance in the Jackson data is yet higher than the variance from Blodgett.

Examining just even-aged plots last harvest 100 years ago:

The coefficient of variation of carbon in live trees = 46 %, based on 39 plots

95 % confidence interval as a proportion of the mean = 18 %

The minimum number of plots required to target 7% measurement error with 95 % confidence = 180

This is the number of plots that would be required to precisely target the measurement of carbon stocks if similar procedures were followed to those used by JSDF. A sampling design implemented by us would target a higher density of plots in the strata of interest and would consequently expect to achieve a lower level of variation and consequently a lower number of required plots.

Plot densities of one plot every eight or nine hectares is insufficient to answer most issues, especially with regard to carbon. It could be advantageous to employ a compartment system as is found at BFRS with accurately georeferenced plots linked to the forestry practice employed in any one place in the forest.

A.2. Number of Plots

The cost of measuring and monitoring carbon in forests is highly related to the number of plots needed to achieve specified precision levels—the higher precision desired the more plots needed. In this section we show how the precision level for these two case studies influence the number of plots needed and thus cost.

A.2.1 Blodgett Forest

The BFRS inventory data for live aboveground trees is used as the source of the level of variation and the calculations for a forest 80 years of age are taken as appropriate for the creation of a long-term sampling plan. In Figure A.1 the number of plots required to target a variety of precision levels is illustrated. As aboveground live biomass is the dominant biomass component, it is this component that can be used to dictate the number of measurement plots.

Although a measuring plan specifically designed for the purpose of carbon evaluation might yield different levels of variation, using the data available here indicates that if 5 % precision were desired then 289 plots should be established. This falls to 72 if 10 % precision is acceptable or just 8 plots if no more than 30 % precision is required.

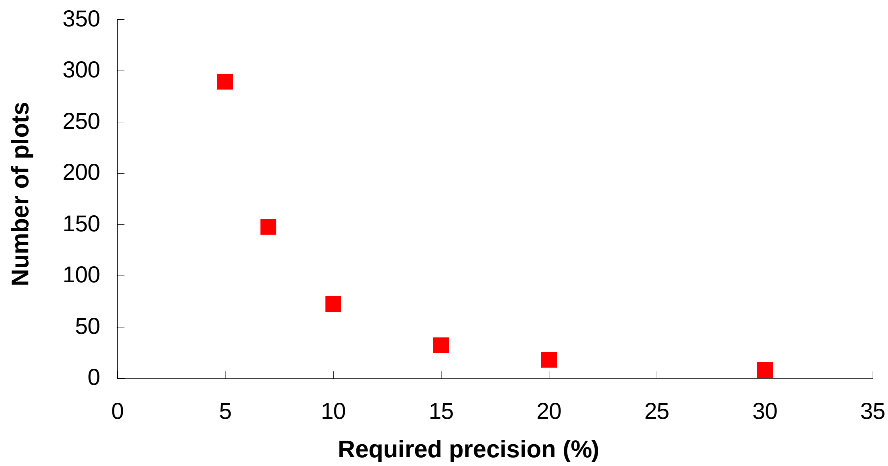

Figure A.1. The number of measurement plots required to measure carbon density to a given level of precision (confidence interval as a % of mean) in mixed Sierran conifer forest

A.2.2. Jackson Forest

The JDSF inventory data for aboveground live biomass is used as the source of the level of variation and the calculations for a forest 100 years of age are taken as appropriate for the creation of a long-term sampling plan. In Figure A.2 the number of plots required to target a variety of precision levels is illustrated. As aboveground live biomass is the dominant biomass component, it is this component that can be used to dictate the number of measurement plots.

Although a measuring plan specifically designed for the purpose of carbon evaluation might yield different levels of variation, using the data available here indicates that if 5 % precision were desired then 357 plots should be established. This falls to 89 if 10 % precision is acceptable or just 10 plots if no more than 30 % precision is required.

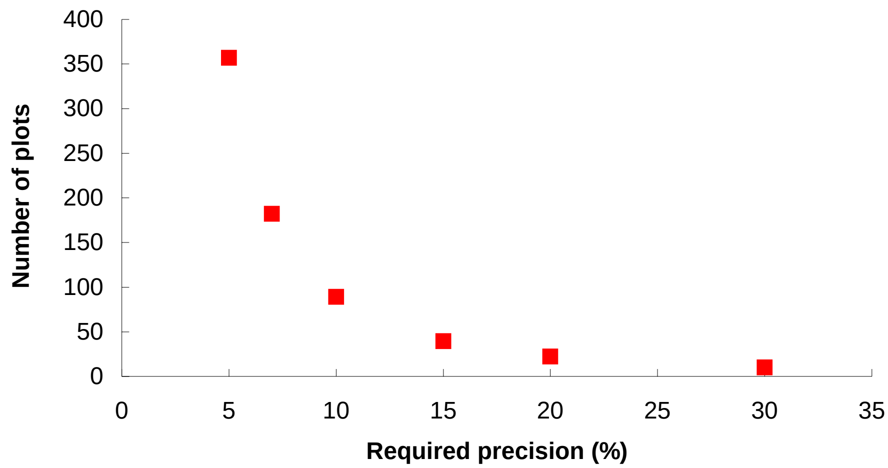

Figure A.2. The number of measurement plots required to measure carbon density to a given level of precision (confidence interval as a % of mean) in coastal redwood forest

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